# POWER QUALITY GUIDELINES FOR ENERGY-EFFICIENT DEVICE APPLICATION

CONSULTANT REPORT

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# Power Quality Guidelines for Energy-Efficient Device Application

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# EXECUTIVE SUMMARY

Energy efficiency and conservation are crucial for a balanced energy policy for the nation in general and the state of California. Widespread adoption of technologies such as energy-efficient motors, adjustable-speed drives, and improved-efficiency lighting will be the key in achieving self-sufficiency and a balanced energy policy that takes into account both supply-side and demand-side measures.

To achieve the full benefit of their use, these energy-efficient technologies must be applied intelligently and with clear recognition of the impacts some of these technologies may have on power quality and reliability. Gaining acceptance of new energy-saving technologies by the general populace is also key to realizing a sound energy program for the state of California. With that in mind, EPRI and the California Energy Commission (CEC) have worked to develop this guidebook to promote better understanding of the potential benefits of energy-saving technologies and also their power quality and reliability implications.

## Objectives

This guidebook has three primary objectives.

1. **To provide guidelines for minimizing any undesirable power quality impacts of energy-saving technologies**

The first objective is to provide guidelines for minimizing any power quality impacts resulting from application of energy-saving technologies with regards to motors and lighting. The primary focus is on energy-efficient motors, adjustable-speed drives, and electronic ballast for lighting. These are proven energy-saving measures, and widespread adoption of these technologies will go a long way in alleviating California's energy crisis. It is crucial that misapplication of these technologies—especially those that would result in power quality side effects—be minimized to ensure that customers are not turned off by these technologies. The guidebook provides explanations of possible side effects and offers suggested mitigation methods.

2. **To provide an understanding of the energy-savings potential of power quality-related technologies**

The second objective of the guidebook is to offer practical guidelines for customers regarding energy-savings potential for some electrical devices whose primary application is *not* for energy savings. However, energy savings is often used as one of the selling features for these devices and customers need to have a clear understanding of the energy-saving potential of these types of technologies. These include:

- Surge protective devices (SPDs) or transient voltage surge suppressors (TVSS),

- Harmonic filters,
- Power factor correction capacitors, and
- Electronic soft starters for motors.

**3. To provide guidelines for evaluating “black box” technologies**

The final objective of this guidebook is to provide customers with practical guidelines on evaluating the energy-saving potential for some “black-box” electrical products that claim to save energy and products that can be grouped generally as motor voltage controllers. The energy-saving potential for some of these technologies is very much application dependent in some cases and questionable in others. It is important for customers to have a basic understanding of the characteristics of all these products. A misunderstanding of the energy-saving potential for these technologies can cause a negative feeling among customers that may stop them from aggressively pursuing other clearly proven energy-saving measures such as energy-efficient motors, adjustable-speed drives, and energy-efficient lighting.

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## Background

Energy efficiency and conservation are crucial for a balanced energy policy for the nation in general and the state of California. Widespread adoption of energy-efficient technologies such as energy-efficient motors, adjustable-speed drives, and improved-efficiency lighting will be the key in achieving self sufficiency and a balanced energy policy that takes into account both supply-side and demand-side measures.

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# 2
# THE POWER QUALITY IMPACT OF ENERGY-EFFICIENT MOTORS

## Introduction

Efficient use of energy enables commercial and industrial companies to minimize production costs, increase profits, and thereby remain competitive. The main target for energy-efficient measures in the industrial sector is the induction motor, which uses most of the energy delivered to industrial facilities. In fact, studies commissioned by the U.S. Department of Energy show that electric motors consume almost 60 percent of all power generated in the United States. As shown in Figure 2-1, some industries are so motor-rich that motors consume more than 92 percent of the supplied energy.

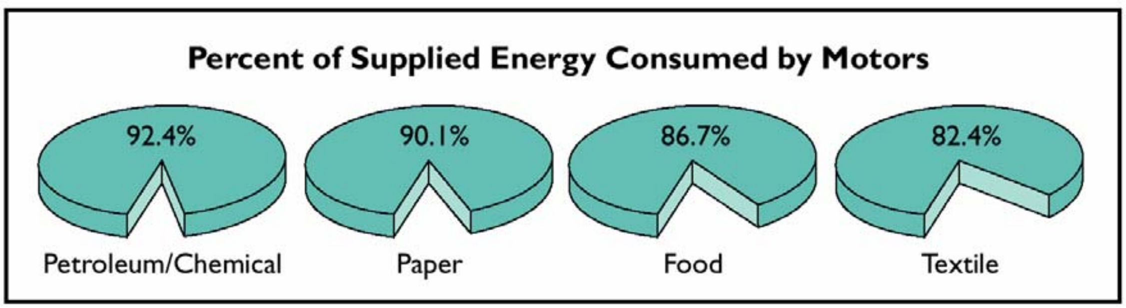



**Figure 2-1**
**Motors Consume an Average of 88 Percent of Supplied Energy Across Four Major Industries**

In many respects, it is most appropriate to think of electric motors as "energy conversion" devices—converting electrical energy into mechanical energy. During this conversion, some energy is lost to vibration, noise, and heat. In an era of energy efficiency and conservation, any device characterized by its energy losses becomes a prime target for improved energy performance. Compelled by federal law and standards organizations, manufacturers of induction motors are thus designing and building more efficient motors (that is, motors with lower energy losses).

In October 1973, oil embargoes of petroleum-rich Middle-Eastern countries caused oil prices to surge and initiated an energy crisis in the United States. High gasoline prices and long lines at the gasoline pumps led legislators to reconcile the dependence of the United States on foreign petroleum and the high demand for electric energy. Since that time, the U.S. Department of Energy has worked to develop energy-saving measures. On October 24, 1992, Congress passed

Public Law 102-486, the Energy Policy Act (EPAct), which mandates strict energy-efficiency standards for electrical appliances and equipment, including industrial, general-purpose electric motors.

EPAct requires that the most commonly used types of induction motors (general-purpose, Design-A and Design-B) meet the higher nominal full-load efficiency requirements defined in Table 12-10 of the National Electrical Manufacturers Association (NEMA) Standard MG-1-1993*, Motors and Generators*. As a result of EPAct, almost all motor manufacturers now offer a line of energy-efficient, Design-B motors that meet or exceed this energy-efficiency requirement. Because today's general-purpose induction motors must meet the energy efficiency levels of the EPAct, yesterday's *energy-efficient* or *premium- efficiency* motors are today's *standard-efficiency* models. Because of EPAct, today's standard-efficiency motor is ½ to 4 percentage points higher in efficiency than older, standard-efficiency induction motors.

In 1994, NEMA issued a revision to MG-1-1993, which included specifications for a new, higher efficiency motor designated NEMA Design-E. The nominal, full-load efficiency requirements listed for a Design-E induction motor in Table 12-11 of the NEMA revision exceed the efficiency requirements stipulated by EPAct. Therefore, Design-E motors not only qualify as EPAct energy-efficient motors, but also as a premium-efficiency motor—a term not precisely defined by NEMA but understood in the motors industry to mean higher efficiency than required by law. **Error! Reference source not found.** shows the full-load, nominal efficiencies for 1800-rpm, EPAct, energy-efficient induction motors and NEMA Design-E, premium-efficiency induction motors.

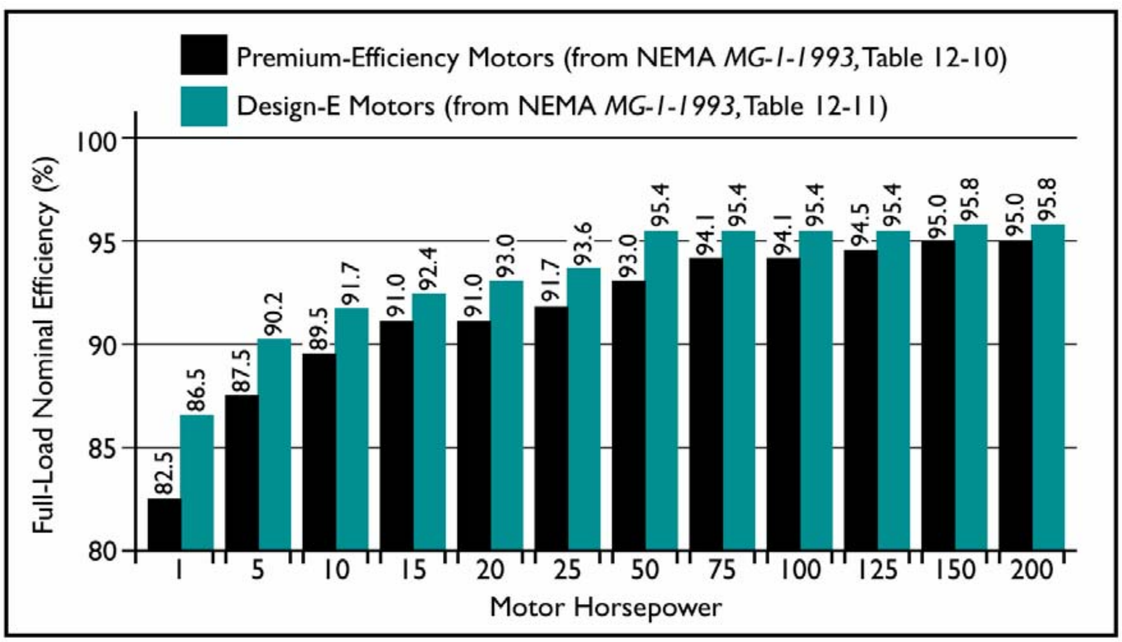



**Figure 2-2**
**Minimum Efficiency Values for 1800-rpm, Energy-Efficient Motors and NEMA Design-E Motors [480-Volt and Totally Enclosed, Fan Cooled (TEFC)]**

## Improving Induction Motor Efficiency

Motor efficiency is the ratio of a motor's mechanical power output to its electrical power input. To improve motor efficiency, motor losses must be reduced. As shown in Figure 2-3, motor losses can be divided into five major types:

1. Stator losses caused by resistance within the stator windings to the flow of electric current (also called stator $I^2R$ losses).

2. Rotor losses caused by resistance within the rotor bars or windings to the flow of induced current (also called rotor $I^2R$ losses).

3. Core losses result from inefficiencies in creating magnetic fields in the laminated metal of the stator and rotor including magnetic hysteresis (resistance to changing magnetic fields) and eddy currents (that circulate inside each core lamination).

4. Windage and friction losses due to air resistance, the motor's internal fan, and friction within the bearings.

Stray losses are all other losses and include such difficult-to-quantify inefficiencies as stray magnetic flux (flux that doesn't link the stator and rotor fields), magnetic resistance in the air gap between the stator and rotor, noise, and vibration.

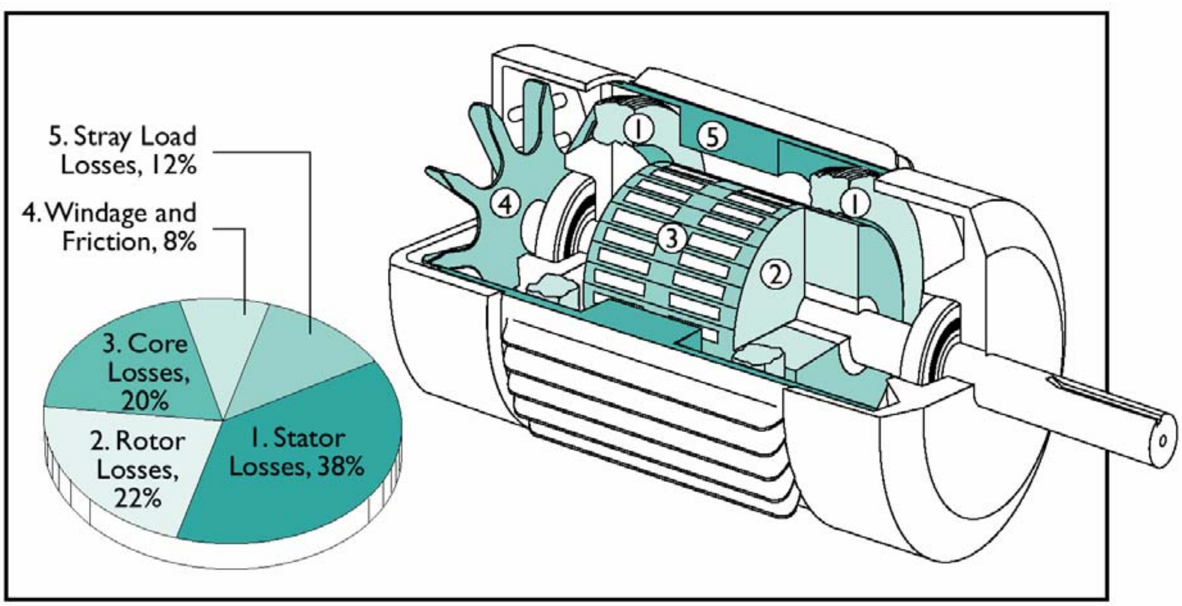



**Figure 2-3**
**Five Areas of Motor Losses and Their Typical Distribution (as a Percent of Total)**

Motor manufacturers typically employ one or more of the following methods to reduce the losses of an induction motor:

- Stator Losses: Increasing the cross-section of the stator conductors will decrease the resistance of the stator windings, thus reducing $I^2R$ losses.
- Rotor Losses: Increasing the cross-section of the rotor conductor bars (or windings) and end rings will decrease the resistance of the rotor, thus reducing $I^2R$ losses.
- Core Losses: Using special, "high-permeability" magnetic steel in the core laminations can reduce hysteresis losses. Using very thin laminations that impede wasteful circulating currents can reduce eddy currents.
- Windage and Friction Losses: Using a heat-treatment process, improving the surface finishes on rotors, and optimizing the design of fans will decrease windage losses. Using low-loss, high-quality bearings can minimize friction losses.
- Stray Losses: Making the air gap between the stator and rotor as narrow as possible is the most common method for reducing stray losses.

Electric motors can be found in almost every residential, commercial, and industrial facility. However, the industrial market is by far the largest consumer of electric power and relies heavily on electric motors. A 1997 market study commissioned by the U.S. Department of Energy (DOE)[1] found that electric motors account for 69 percent of the industrial energy consumed in the United States during 1994. Moreover, 25 percent of all electricity sold in the United States was consumed by process motor-systems in 1994.

Improving the efficiency of process motor-systems has by far the largest energy-saving potential in the industrial sector.

### *Steps to Improve Motor Efficiency*

A number of opportunities exist for increasing production efficiency. These can be broken down into three main categories:

1. Improving motor efficiency
2. Correcting for motor oversizing
3. Improving the motor-system efficiency

According to the DOE study[1], the combined potential for improving energy efficiency for all three categories listed above is nearly 15 percent.

Improvements in motor efficiency alone (the first category shown above) could account for a 4.3 percent improvement, an energy savings of 24.6 GWh. During the DOE study, surveys of on-site industrial facilities revealed several key facts:

[1] *United States Industrial Motor Systems Market Assessment*, Office of Industrial Technology, US Dept. of Energy, December 1998.

- Only 19 percent of facilities reported that they were aware of the availability of premium-efficiency motors as specified in EPAct 1992
- Only 11 percent of the facilities have written specifications for purchasing motors. Only two-thirds of the ones with written specifications have specifications for motor efficiency

Correcting for motor oversizing (the second category shown above) could accounts for a 1.2 percent improvement, an energy savings of 6.8 GWh. Survey results also revealed that industrial facilities most often use the size of a failed motor as a key specification when deciding on a replacement. Approximately 30 percent actually use the size of the failed motor as the only factor.

Motor-system improvements (the third category shown above) have the largest potential for increased energy efficiency and reduced energy costs at 10.5 percent. Nearly two-thirds of the potential energy-efficiency increase can be achieved through motor-system improvements. The DOE survey found that improvements in motor-system efficiency are not undertaken very often at smaller facilities. Motor-system improvements include increasing piping diameter to reduce friction in pumping applications, equalizing flow over a production cycle using holding tanks, eliminating unnecessary bypass loops and other unnecessary flows, and replacing worn or damaged mechanical parts. The use of electronic, variable-speed drives to control process-motor speed is another major part of improving motor-system efficiency.

## Potential Impacts of Energy-Efficient Motors on Power Quality Issues

When making a decision to install an energy-efficient motor, end users should be aware of performance-related issues, especially for Design-E motors. These issues include starting current, motor starters, nuisance tripping, voltage drops, full-load speed, starting torque, and the operation of energy-efficient motors with adjustable-speed drives.

### *Reduced Winding Resistance – An Important Characteristic of Energy-Efficient Motors*

One important issue for users of new, high-efficiency induction motors is the electrical resistance of the motor's stator and rotor windings or bars. For example, to reduce the stator and rotor $I^2R$ losses in induction motors, manufacturers seek to reduce the resistance of motor windings and bars by increasing their cross-section. This reduced resistance may cause energy-efficient motors to draw a higher inrush current, higher starting current, and more unbalanced current for a given voltage unbalance. It may also make the motor more susceptible to undesirable influence from voltage harmonics.

While the use of energy-efficient motors can provide significant benefits, end users should be aware of the impacts on power quality that can emerge from differences between standard-efficiency, premium-efficiency, and Design-E induction motors. In addition, the quality of electric power supply can have an impact on the performance of energy-efficient motor systems.

### Higher Starting Current

A principal side effect of reducing the internal resistance of premium-efficiency motors is higher starting current—the initial electrical current drawn by the motor when it is first energized. Until a motor starts to rotate, the only resistance at its terminals is the winding impedance. Therefore, because energy-efficient motors have less winding resistance than standard-efficiency motors, the starting current of energy-efficient motors is typically higher.

As shown in Figure 2-4, the starting current of a motor is composed of a series of two types of current. The first type, called momentary inrush current, is similar to the inrush current associated with the core of a transformer when it is first being energized. Momentary inrush current lasts for the first half cycle or so (0.0083 seconds) of the starting current. For some Design-E induction motors, this current can be as high as eight times the motor's full-load current. This compares to levels of five to six times full-load current typically exhibited by non-Design-E motors.

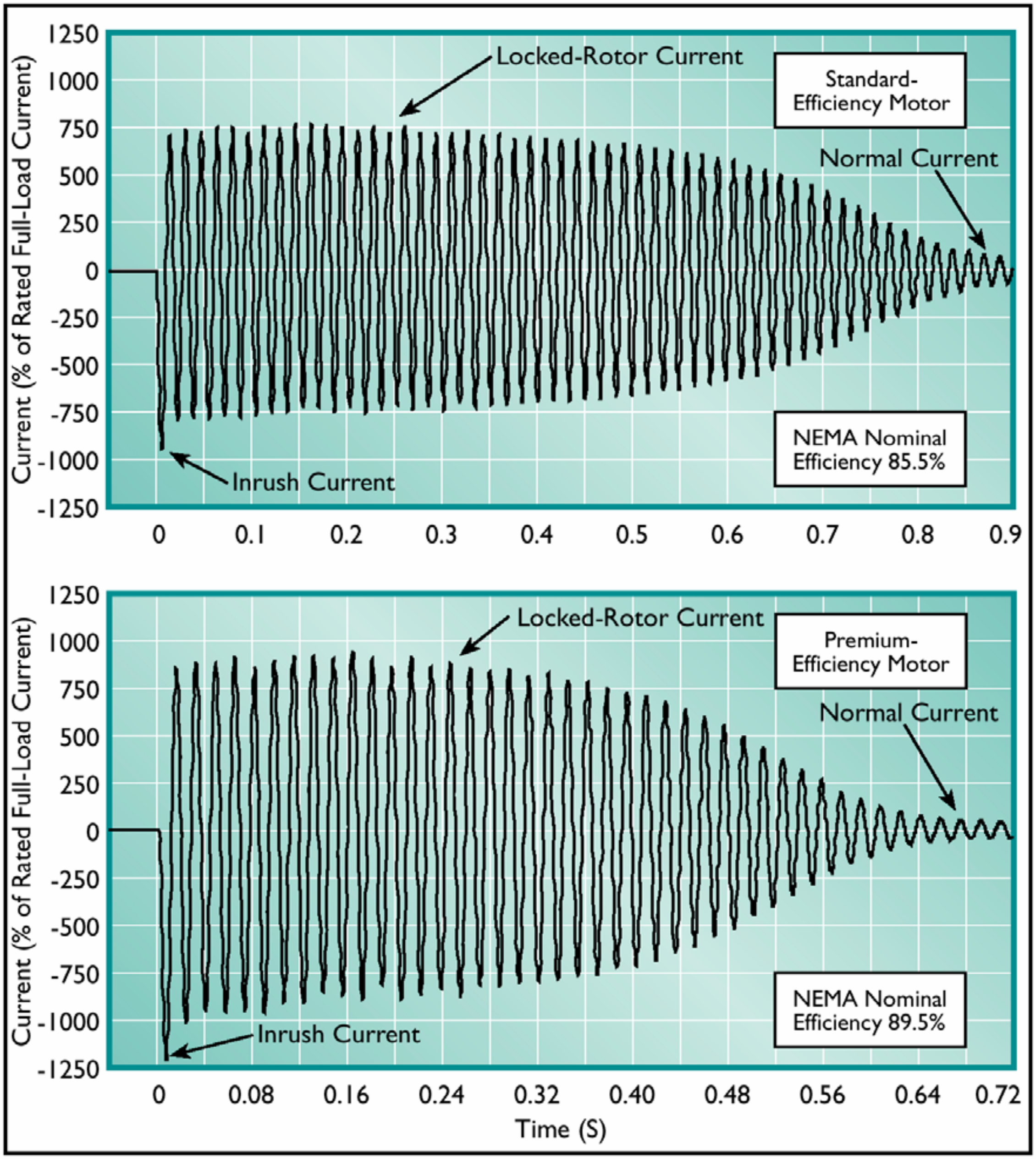



**Figure 2-4**
**Momentary Inrush and Locked-Rotor Current during Motor Starting for a Standard-Efficiency and a Premium-Efficiency, 5-Horsepower Motor**

The second type of starting current, called locked-rotor current, is the result of the motor being started from a stopped (non-rotating) condition. As shown in Figure 2-4, the locked-rotor current begins when the motor is first energized and then tapers off to full-load current (or some percentage of full load current, depending on the motor's loading) once the motor has accelerated to full speed. During acceleration, the motor's self-generated internal voltage, called "back EMF" (short for back electromotive force), begins to oppose the applied utility voltage. Eventually, the motor current decreases to a level necessary to keep the motor turning under load. The duration of locked-rotor current—anywhere from a few electrical cycles to several seconds—depends upon how long it takes the motor to accelerate to full speed. Variables affecting this include the size of the motor, the “stiffness” of the voltage source energizing the motor, and the inertia of the motor’s load.

The average starting current of typical standard-efficiency motors is about five to six times the rated full-load current (see IEEE Standard 141-1993, *IEEE Recommended Practice for Electric Power Distribution for Industrial Plants*). The locked-rotor current of a premium-efficiency motor can be as high as eight times the rated full-load current, and the locked-rotor current of a Design-E motor can be as high as nine times. NEMA MG-1-1993, Revision 3, specifies a maximum locked-rotor current for Design-B as well as Design-E motors. Because locked-rotor current depends upon the voltage rating of a motor, this information is often presented as locked-rotor kVA/HP. **Error! Reference source not found.** shows the maximum locked-rotor kVA/HP allowed by NEMA MG-1-1993 for a standard-efficiency Design-B motor and a Design-E motor.

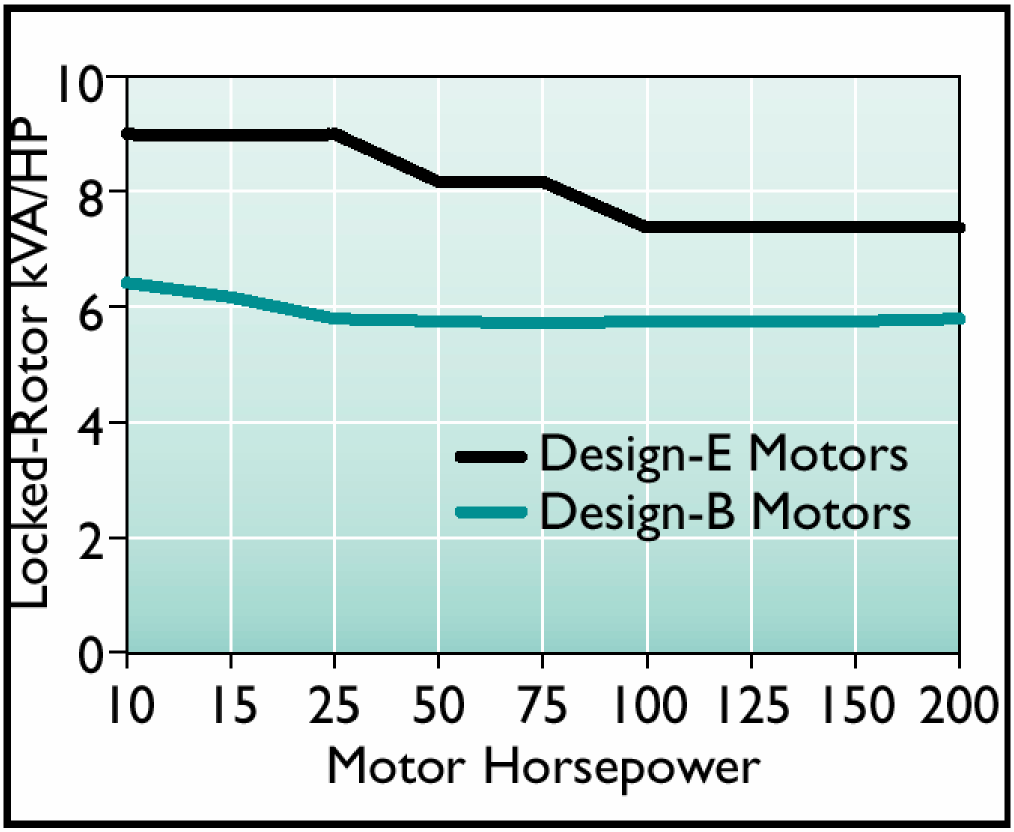



**Figure 2-5**
**Maximum Locked-Rotor kVA/HP for Standard-Efficiency Design-B and Design-E Motors**

### *Nuisance Tripping of Energy-Efficient Induction Motors*

One unfortunate manifestation of high starting currents with high-efficiency motors is it can cause nuisance tripping of circuit breakers, particularly in the case of instantaneous-trip circuit breakers—protective devices that disconnect a motor to protect it and other equipment. Nuisance tripping of energy-efficient motors can be avoided by increasing the settings of overload protective devices to higher levels. The National Electrical Code (NEC) recommends setting the trip level of a circuit breaker at 800 percent of the motor full-load current for standard-efficiency motors and 1100 percent for Design-E motors. However, Section 430-52 of the 1996 revisions to the NEC takes the higher inrush current of energy-efficient motors into account by allowing 1300 percent of a motor's full-load current as the trip setting for non-Design-E motors and up to 1700 percent for Design-E motors. These exceptions are permitted if either a field trial or engineering evaluation indicates that the basic rule of 800-percent setting for non-Design-E and 1100-percent setting for Design-E motors will result in nuisance tripping as the motor starts.

### *Momentary Voltage Drop When Starting Energy-Efficient Induction Motors*

All induction motors, with their high initial starting currents, can cause a facility's supply voltage level to dip—particularly if the electric supply is marginal or stressed (for example, at the end of a very long utility feeder or operating very near full capacity). Calculating voltage drop during motor starting is usually done during the engineering-evaluation stage of motor installation, with a 10-percent, momentary voltage drop generally considered a maximum. However, replacing standard-efficiency motors with energy-efficient motors may result in higher, and perhaps excessive, voltage drops. The higher starting current of energy-efficient motors results in more severe drops in the utilization voltage, which may prevent the motor from starting and adversely affect other equipment connected to the same bus. For example, high-intensity discharge lighting, which is sensitive to voltage variations, may drop out during the starting of an energy-efficient motor. The amount of voltage drop at the point of motor connection depends upon the amplitude of the starting current and the upstream impedance, which is mostly the impedance of distribution lines, cables, and transformers.

### *Selecting Starters for Energy-Efficient Induction Motors*

When standard-efficiency motors are replaced by energy-efficient motors, the existing motor starters may not be able to handle the higher starting current.[2] Therefore, installing energy-efficient motors may require the use of starters that are specially designed for handling higher inrush current or the derating[3] of standard motor starters

The 1996 revision to NEC provides clear guidance for rating motor starters and disconnecting means for Design-E motors. Conventional motor starters and other motor controllers can be used with Design-E motors as long as the rating of the starter exceeds that of the motor by a factor of 1.4 when the motor is between 3 and 100 horsepower and by a factor of 1.3 for larger motors

[2] Energy-efficient motors are defined by the standard NEMA MG-1-1993, which sets forth energy efficiency thresholds for general purpose induction motors in common horsepower sizes from 1 hp to 200 hp. The most common NEMA designs used for energy-efficient motors are Design B and Design E.

[3] Derating the perforance levels of electrical equipment is common practice and recognizes that certain operational or environmental circumstances may prevent equipment from performing safely at normal rated output levels. Examples of factors that may lead to derating include altitude, ambient temperature and other weather conditions, contamination, and overload conditions. Practically, derating requires the installation of a larger (or otherwise more capable) piece of equipment than would normally be required (for example, using a 100-hp motor where a 75-hp motor might have served under more favorable conditions).

(see NEC Section 430-109 Ex. 1 [new] and Section 430-83(a) Ex. 1 [new]). This derating factor takes into account that the locked-rotor current for energy-efficient motors can be higher than for standard-efficiency motors by a factor of 1.3 to 1.4 times. Of course, motor controllers that are designed for Design-E motors can be used without derating them.

The guidelines for Design-B premium-efficiency motors are not clear because the locked-rotor current varies significantly by manufacturer. For Design-B premium-efficiency motors, the end user should obtain data on the locked-rotor current from the manufacturer and install motor controllers that are capable of handling that current.

## Effects of Power Quality on Energy-Efficient Induction Motors

While induction motors can precipitate power quality problems, they can also be victims of poor power quality. The following sections discuss the effect of voltage unbalance and harmonic voltage distortion on energy-efficient motors and other equipment connected to the same bus.

### *Effects of Voltage Unbalance on Induction Motors*

Electric power is almost universally distributed in the form of three-phase power—consisting of at least three conductors operating at the same (or nearly the same) voltage but 120 degrees out of phase. Electrical machines that use three phase power—such as the majority of induction motors—are designed to have the three phase voltages equal, or nearly so. When the phase voltages are not equal, significant problems can occur, often manifesting in two of the biggest threats to the longevity of rotating equipment: excessive heat and vibration.

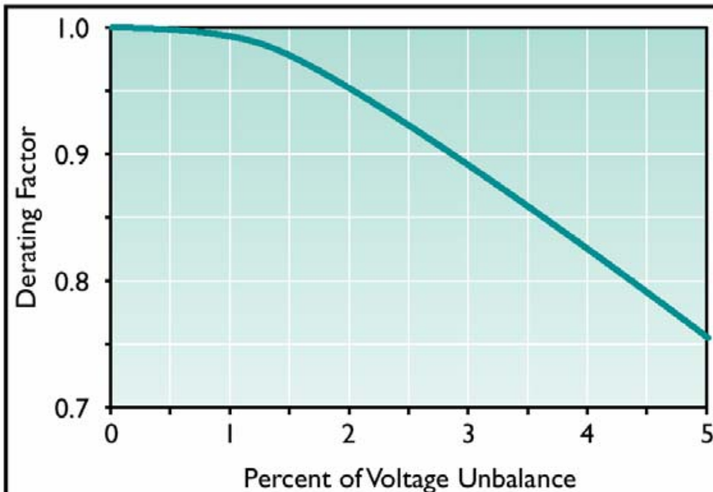
#### Temperature Rise Because of Voltage Unbalance

An unbalanced, three-phase voltage causes three-phase motors to draw unbalanced current—a current that contains a negative-sequence component (one that creates magnetic fields that oppose the motor's normal direction of rotation and can cause the rotor of a motor to overheat). In fact, the temperature rise caused by unbalanced current is much greater than the rise caused by the motor current alone. A voltage unbalance results when phase voltages at the point of utilization are unequal. Common causes of voltage unbalance include (1) faulty operation of automatic, power-factor-correction equipment and voltage regulators in the utility distribution lines; (2) unevenly distributed, single-phase loads in a facility; and (3) an unbalanced transformer bank. According to Appendix D of American National Standards Institute (ANSI) Standard C84.1, *Electric Power Systems and Equipment*, approximately 98 percent of surveyed electric power-supply systems are within 3 percent voltage unbalance, with 66 percent of the systems at 1 percent or less. ANSI C84.1 recommends that electric power-supply systems have no more than 3 percent voltage unbalance when measured at the revenue meter during no-load conditions. NEMA Standard MG 1-14.35 recommends derating an induction motor when the voltage unbalance exceeds 1 percent and recommends not operating a motor at all when the voltage unbalance exceeds 5 percent.

## Derating Motors Because of Voltage Unbalance

Operating a motor during a voltage unbalance generally requires the motor to be derated to ensure long life. If the motor is not equipped with an embedded temperature detector or if incorporating the detector into a protection scheme is not feasible, then the end user should consult with the motor manufacturer to determine the maximum level of current unbalance that is acceptable for all loading conditions. For example, the effect of a 10-percent current unbalance on a motor that is fully loaded is greater than the effect on the same motor if the motor is loaded at only 50 percent.

Essentially, the operation of a motor under unbalanced voltage conditions requires that the motor be derated. For standard motors, NEMA provides guidance for derating. For voltage unbalances between 1 and 5 percent, NEMA suggests derating motors according to the graph shown in Figure 2-6. NEMA has not yet established a derating graph for energy-efficient motors. However, because energy-efficient motors have lower losses during balanced as well as unbalanced voltage conditions, applying the derating graph in Figure 2-6 to energy-efficient motors will yield conservative derating factors.




| Voltage Unbalance | Approximate Derating |
|---|---|
| 1% | None |
| 2% | 95% |
| 3% | 88% |
| 4% | 82% |
| 5% | 75% |

For motors rated greater than 500 horsepower, derating must be calculated in consultation with the vendor.

**Figure 2-6**
**Derating Graph and Table for Induction Motors Based Upon Percent of Voltage Unbalance (from National Electrical Manufacturers Association MG-1-1993)**

### *Unbalanced Currents In Induction Motors*

When a standard-efficiency motor is replaced with an energy-efficient motor, the protection scheme against excessive unbalanced current may cause nuisance tripping, especially when the scheme is configured to disconnect the motor based upon the percent of relative current unbalance and not the temperature of the motor. To overcome nuisance tripping caused by current unbalance, the end user has two options:

**Monitor the Temperature.** The best way to protect a motor stator against unbalanced current is to monitor the temperature rise of the motor. Many motors, especially large motors, are equipped with an embedded temperature detector. If a protection scheme were to include an input from a temperature detector, the motor can be taken offline when the motor temperature exceeds a predetermined level rather than taken offline when the current unbalance exceeds a predetermined level.

**Provide Time Delay.** Most of the faults in a utility distribution system are single-phase. The voltage sags resulting from these faults are usually very unbalanced, causing a severe voltage unbalance at the motor terminals. However, the duration of a voltage sag is typically only a few cycles, the time it takes utility protection devices to clear a fault. In some cases, a motor will trip during a momentary voltage unbalance because of the resulting current unbalance. Also, sensitive relays in the motor-protection circuit may drop out, disconnecting the motor from the line. To prevent nuisance motor tripping or disconnection during unbalanced voltage sags, a time delay can be incorporated into the motor-protection circuit.

### *Effects of Harmonic Voltage Distortion on Induction Motors*

One effect of the widespread use of power electronic converters such as variable-frequency drives is an increase in voltage distortion—the presence of unwanted frequencies in the voltage other that the normal 60-Hz fundamental. The higher frequencies associated with harmonic voltage distortion (usually in the range of 300 to 3000 Hz) can increase energy losses in iron and copper, resulting in increased motor heating and higher operating temperatures. Typically, background harmonic distortion (harmonic distortion that already exists in a wiring system) is comprised of harmonics of odd multiples such as $3^{rd}$, $5^{th}$, and $7^{th}$ harmonics. As with voltage unbalance, some specific harmonic components such as the $5^{th}$ and $11^{th}$ can cause the rotor to dramatically overheat.

To compensate for harmonic voltage distortion, end users can derate induction motors. In the absence of any established guidelines for energy-efficient motors, end users should follow the procedure for derating motors in NEMA MG-1-1993, Section IV, Part 30. Following this procedure will typically yield conservative derating factors for the operation of energy-efficient motors under distorted-voltage conditions.

## Conclusion

Promotion of energy-saving measures by the federal government and electric utilities and the enactment of those measures by end users are enabling energy-efficient motors to quickly replace standard-efficiency induction motors. However, unless application engineers become familiar with the potential consequences of using energy-efficient motors, this transition may catch some people off guard and discourage them from using premium-efficiency and Design-E motors. By anticipating issues related to power quality and performance, end users can successfully install and maintain energy-efficient motors, thereby reducing energy costs and complying with federal law.

# 3
# THE POWER QUALITY IMPACT OF ADJUSTABLE-SPEED DRIVES

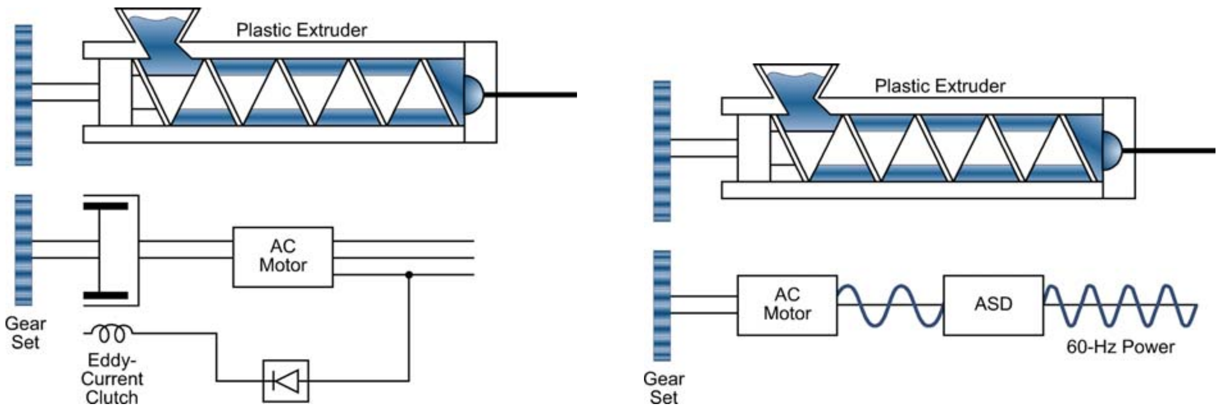
With the advent of today's microprocessor and power electronics technologies, there are alternatives to inefficient mechanical process controls. The adjustable-speed drive (ASD)—also called a variable-speed drive (VSD), variable-frequency drive (VFD), inverter drive, or motor drive—is a highly efficient process control device that enables induction motors, which normally operate at only a single, constant speed, to operate at an adjustable speed. As a result, ASDs are replacing mechanical control devices in industrial applications. ASDs provide a flexible and efficient motor-control scheme, allowing motor speed and torque to be controlled with much higher precision and accuracy. Furthermore, because motor speed can now be adjusted to match the needs of the load or process, ASDs can decrease system losses and increase system efficiencies when processes operate at reduced rates.

Although ASDs can greatly improve the efficiency and productivity of motor-driven systems, they, like induction motors, cause and suffer from power quality problems.

## Improving System Efficiency With Adjustable-Speed Drives

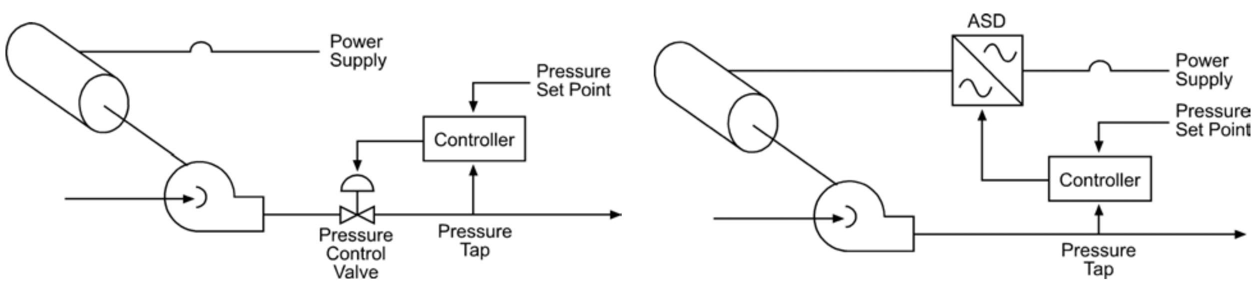
The use of ASDs allows direct connection of motors to the loads. This control technique can significantly improve the motor-system efficiency by allowing reduction in speed (which inherently saves energy) or through elimination of alternative and wasteful means of regulating output.

In the past, processes were often controlled by inefficient mechanical means, such as vanes, bypass valves, throttling vales, and dampers. With the application of an ASD, processes are controlled directly by varying the motor's speed and torque. Figure 3-1 and Figure 3-2 show the replacement of mechanical controls with an ASD.




Mechanical Controls | ASD Control

**Figure 3-1**
**Replacement of Mechanical Controls with an Adjustable-Speed Drive in a Plastic-Extruder Process**




Mechanical Controls | ASD Control

**Figure 3-2**
**Replacement of Mechanical Controls with an Adjustable-Speed Drive to Control the Flow of Material in a Process**

In addition to eliminating inefficient control elements like valves and vane, ASDs also allow dramatic energy savings by reducing the speed of fans and pumps so that only the flow necessary for the process is produced. These loads—so called "cube-law load"—are important because the energy used by most fans and pumps increases eight-fold for each doubling of speed, as shown in Figure 3-3.

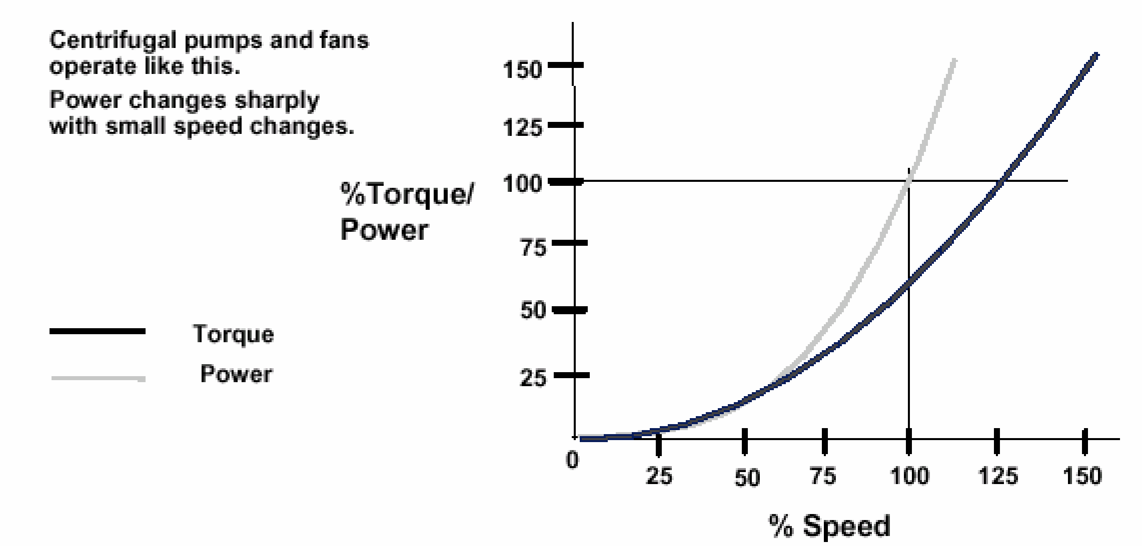



**Figure 3-3**
**Cube-Law Loads (Like Most Fans and Pumps) Use Much More Energy as Speed Increases**

## The Structure of Adjustable-Speed Drives

All ASDs have the same basic structure, which includes a rectifier, filter, and inverter. The rectifier converts three-phase AC line power to DC power. The components used in the rectifier are typically thyristors or diodes. The filter sits between the rectifier and inverter and provides harmonic and power ripple filter (using inductors or chokes) as well as power storage (using capacitors). These components work to smooth and regulate, respectively, the current and voltage supplied to the motor. The inverter portion typically consists of thyristors or transistors that are carefully controlled to sequence the proper voltage and current to the phase windings of the motor, depending on the speed and load required.

Present-day economics favor pulse-width modulated drives for applications under 200 HP and, in most cases, these drives will provide excellent service. In both retrofit and new applications, the user should consider heating and cabling distance to make sure the supplier will guarantee long-term performance. Some applications may also use the older, but very reliable, six-step voltage-source inverter technology. Many thousands of these drives are in service and many companies still design and manufacture them for applications under 200 HP.

## Power Quality Problems Caused by Adjustable-Speed Drives

Like most electronics loads, ASDs can both cause and suffer from power quality problems.

### *Electromagnetic Interference Caused By Adjustable-Speed Drives*

As shown in Figure 3-4, abrupt voltage transitions on the output terminals of an ASD are an inherent source of radiated and conducted electromagnetic interference (EMI). The conducted emission may affect control signals, encoder feedback, communication links for programmable logic controllers, including RS-232, RS 484, remote I/O, and different types of sensors including ultrasonic sensors, bar code/vision systems, weight sensors, and temperature sensors. The most common symptom is erratic operation of the ASD. AM radio reception, radio-controlled operator devices, and televisions are the most susceptible equipment to radiated interference from ASDs.

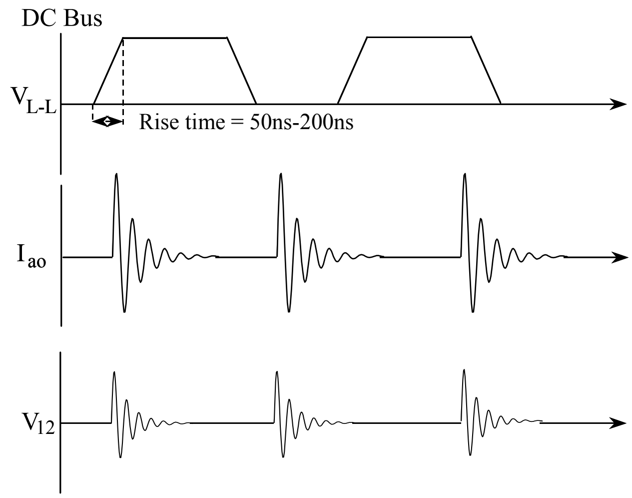



**Figure 3-4**
**Adjustable-Speed Drive Output Voltage**

Customers can require the ASD vendor to meet applicable European Union (EU) standards for drives to avoid potential EMI problems. These standards set the allowable emission limits for conducted and radiated disturbances. Table3-1 shows a summary of emission limits for conducted emissions, and Table 3-2 shows the limits for radiated emissions.

**Table 3-1**
**Limits for Conducted Emissions (150 kHz to 30 MHz)**[4]

| Frequency Range | Residential, Commercial, and Light Industry EN 50081-1 and CISPR 22*, Class B | Industry EN 50081-2 and CISPR 11, Class A |
|---|---|---|
| 150 - 500 kHz | 56 - 46 dBµV (Average) | 66 dBµV (Average) |
| | 66 - 56 dBµV (Quasi-peak) | 79 dBµV (Quasi-peak) |
| 0.5 - 5 MHz | 46 dBµV (Average) | 60 dBµV (Average) |
| | 56 dBµV (Quasi-peak) | 73 dBµV (Quasi-peak) |
| 5 MHz - 30 MHz | 50 dBµV (Average) | 60 dBµV (Average) |
| | 60 dBµV (Quasi-Peak) | 73 dBµV (Quasi-Peak) |

[4] IEC Standard EN50081-1, "Electromagnetic Compatibility Generic Emission Standard - Part 1: Residential, Commercial and Light Industrial" and IEC Standard EN50081-2, "Electromagnetic Compatibility Generic Emission Standard - Part 2: Industry".

* CISPR = Comité International Spécial des Perturbations Radioélectrique

**Table 3-2**
**Limits for Radiated Emissions (30 MHz to 1 GHz)**

| Frequency Range | Residential, Commercial, and Light Industry EN 50081-1 and CISPR 22, Class B | Industry EN 50081-2 and CISPR 11, Class A |
|---|---|---|
| 30 - 230 MHz | 30 dBμV/m @ 10m | 30 dBμV/m @ 10m |
| 230 MHz - 1 GHz | 37 dBμV/m @ 10m | 37 dBμV/m @ 10m |

There are other measures that users of ASDs can take to minimize the EMI impact of ASDs:

- Use a shielded power cable to connect the ASD to the motor. This forces the noise current to flow through the shield back to the inverter before it gets out into the system grid and takes multiple high-frequency paths, which are difficult to track down in an installation.
- Ensure good electrical contact from the installation plate through the installation screws to the metal cabinet of the ASD. Cable clamps should be used instead of twisted shield ends.
- Avoid random lay of unshielded cables in cable troughs.
- Twist the leads to provide a balanced capacitive coupling.
- Use shielded cable to return the noise current flowing in the shield back to the source instead of through the signal leads.
- Maintain at least an eight-inch separation between control and power wires in open air, conduit, or cable trays.
- Use a common-mode choke wound with multiple turns of both signal and shield.
- Use optical isolation modules for control-signal communications.

## Motor Insulation Damage from Adjustable-Speed Drives

Motors connected to ASDs will be subject to repetitive voltage pulses that, under certain circumstances, can be magnified when they reach the motor terminals. Figure 3-5 shows such a magnification where the output voltage pulse at the motor terminals is approximately 1650 volts. The most common symptom is early failure of motors with evidence of turn-to-turn failure of motor insulation. Failure may occur within weeks of installation.

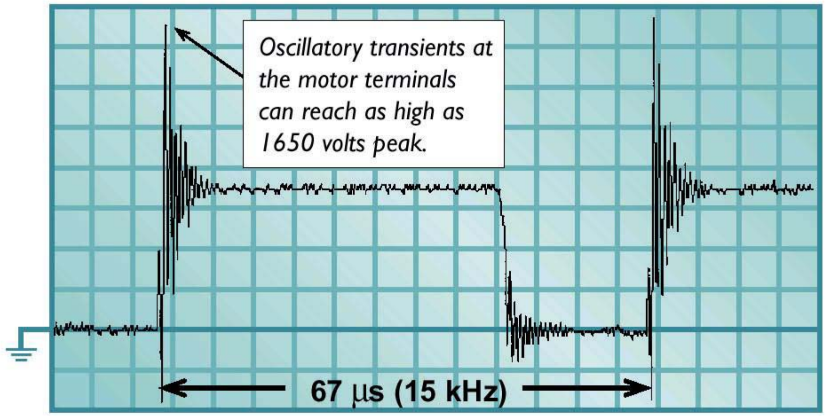



**Figure 3-5**
**Voltage Magnification at Motor Terminals**

Users should clearly request that the motor manufacturer conform to NEMA MG-1-1993, Section IV, Part 31, which defines the requirement for motors that are to be used with ASDs. The motor manufacturer shall provide information to the buyer regarding which one or more of the following key features have been added to augment the motor insulation system to enhance the insulation system of the motor:

- Wire insulation with increased dielectric strength
- Improved insulation on end turns, in the slots, and between phases
- Heavy-duty lacing or taping of end turns
- Extra cycles of varnish dip or vacuum-pressure impregnation
- Maximized copper content
- High-temperature insulation with low thermal-rise levels

In addition, important installation considerations exist for avoiding motor insulation damage from application of ASDs:

- Use a 230-V motor, if possible. Many motors are designed for operation from either 230-V or 460-V supply. In such cases, use of 230-V ASDs and 230-V motors will solve the problem
- If possible, use a switching frequency of less than 5 kHz (if this is a variable that can be changed through programming the drive)

Try to minimize the length of the lead from the drive to the motor. Longer lead length is more likely to cause voltage magnification and thereby increase the stress on motor insulation. Figure 3-6 shows the relationship between lead length and peak voltage at the motor terminals for three different drives

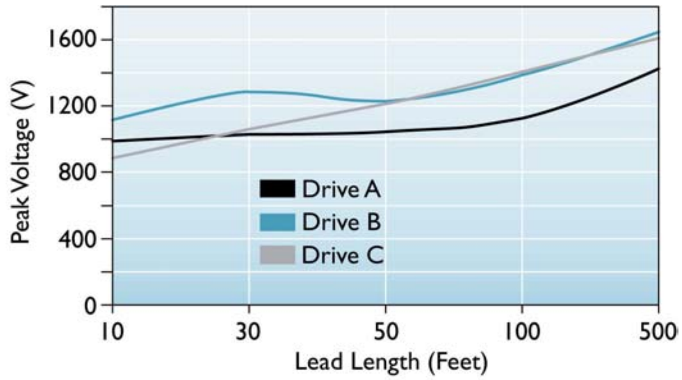



**Figure 3-6**
**Lead Length versus Peak Voltage at the Motor Terminals**

There are basically three different types of filter networks that are commercially available for reducing overvoltages at the motor terminals. These filters are typically installed on the output of the ASD. Line reactors (inductors), resistor-capacitor (RC) snubbers, and resistor-inductor-capacitor (R-L-C) low-pass filters are commonly used to reduce the voltage at the motor terminals. In a majority of cases, a R-L-C low-pass filter has been found to be the most effective filter. However, the user should consult with the ASD vendor to select the filter that will match the specific ASD that is selected for the application.

Whatever type of filter is installed, the user should always measure the voltage at the motor terminals during startup with a proper measurement device in to determine the effectiveness of the filter. If the user believes that the risk factor does not justify using filters, then similar measurements should be performed to ensure that voltage magnification is not occurring.

Figure 3-7 shows the voltage at the motor terminals with and without a low-pass R-L-C filter network installed at the inverter output terminals. Clearly, successful application of these networks will reduce the voltage to a level that may allow standard 600-V motors to be used with inverters. In addition to attenuating the voltage transient, the application of these filters also increases the rise time of the voltage pulses, reducing the possibility of discharge current and bearing problems associated with these discharge currents.

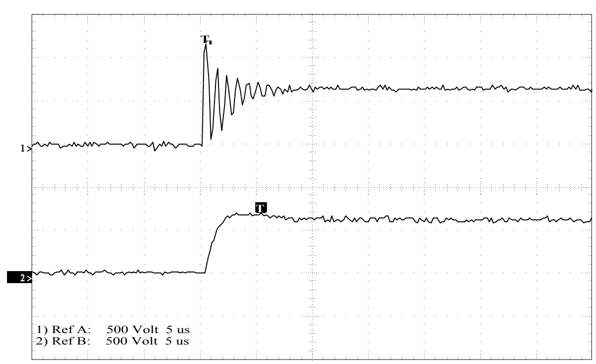



**Figure 3-7**
**Peak-to-Peak Voltage Spike at Motor Terminals *without* R-L-C Filter Network (Upper Graph)**

**and *with* R-L-C Filter Network (Lower Graph) (Vertical Axis: 500 Volts/Division; Horizontal Axis: 5 µs/Division)**

## Motor Bearing Damage from Adjustable-Speed Drives

Motors connected to ASDs can be subject to electrical currents that circulate between the motors stator and rotor. These currents travel using the motor's bearings and bearing surfaces, which can over time pit the bearings in a process referred to as electrical fluting or brinelling.

Audible motor noise and vibration are usually the first obvious symptoms of premature bearing failure. Because excessive noise and vibration can be symptoms of other motor problems, maintenance personnel frequently misdiagnose problems caused by bearing fluting. Usually, the current arcing across the bearings will first damage the smaller idle bearing opposite the end of the shaft connected to the motor load. Idle-bearing failure can occur as soon as six months after the motor has been installed. Discharge current may also damage the bearings of other equipment connected to the motor shaft, such as direct-connected tachometers and gearboxes. In many cases, discharge current will damage the tachometer bearings instead of the motor bearings because the smaller tachometer bearings offer the path of least resistance. Damaged tachometer bearings can cause the tachometer to vibrate, resulting in an erratic signal from the tachometer. **Error! Reference source not found.** shows the classical signature of bearing fluting that is the result of electrostatic discharge between motor shaft and ground through the ball bearing, which is the primary mechanism of bearing damage in motors.

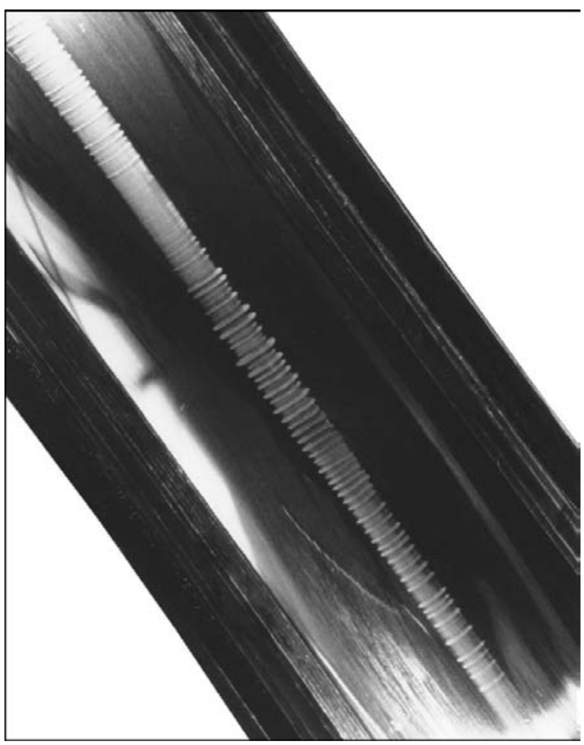


**Figure 3-8**
**Bearing Fluting Caused by Discharge Current Induced by Adjustable–Speed Drive**

A number of approaches exist that can either (1) minimize the incidence of electrical fluting of motors operating on ASDs, or (2) speed the solving of problems if they do occur:

- Purchase a motor-drive system from a single source to minimize the finger pointing between the motor manufacturer and drive manufacturer regarding who is responsible for the problem.
- Specify inverters with a voltage rise time of greater than 0.5 microseconds. While voltage rise time is a function of the lead length, motor size, and the motor loading, the inverter manufacturer should be able to incorporate appropriate filters on the output of the inverter that will ensure that the rise time of the voltage pulses are greater than 0.5 microseconds.
- Unless required for other reasons (such as reduced audible sound level), operate the inverter at a switching frequency less than 8 kHz.
- During commissioning, check for excessive shaft-to-ground voltages (> 300 mV) and the presence of any discharge current.
- Use a filter between the inverter and motor to (1) reduce peak voltages (thus minimizing motor insulation damage) and (2) increase the rise time of the voltage pulses (thus reducing the possibility of discharge current and associated bearing problems).
- Install a shaft grounding system to minimize the magnitude of the shaft voltage and reduce the chance of electrical arcing through bearing lubricant.

## Harmonic Current Injection from Adjustable-Speed Drives

Like any other nonlinear load, ASDs are a potential source of harmonics in the electrical system. The harmonic current injected by an ASD in the system causes voltage distortion. Both the harmonic current and the resulting voltage distortion can cause potential problems. Possible symptoms of ASD-harmonics problems are (1) fuse-blowing in facility power-factor-correction capacitor banks, (2) overheating of transformers and cables, and (3) in some cases, the interference with the operation of other equipment that requires a stable sinusoidal voltage waveform for operation. However, the end user needs to realize that just the presence of harmonics does not necessarily mean that a problem exists. Harmonics only means trouble if the power system is not designed to handle them. Neutral currents with a high harmonic content are a problem only if the neutral is not properly sized. Current harmonics are not a problem to a transformer if it is derated appropriately. Even some voltage distortion less than 8 percent total harmonic distortion (THD) at the point of use is acceptable as long as sensitive equipment is not affected.

Institute of Electrical and Electronics Engineers (IEEE) 519-1992, *Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*, is the most commonly used and misapplied specification for harmonic control for ASDs. IEEE 519-1992 is not a limit for equipment harmonic current injection, but rather a limit of harmonic voltage and current at the point of common coupling (PCC), the place where the consumer and the supplier of electrical power are joined. Specifying that an ASD should meet the IEEE 519-1992 harmonic limits is not an effective harmonic specification for ASDs. Recognizing the fact that harmonics from an ASD can only create problems if the power system is not designed to handle it, an end user should request the ASD vendor or the system integrator to conduct a harmonic analysis and ensure (1) that at the PCC, IEEE 519-1992 harmonic current limits are not violated because of the addition of the ASD, (2) that voltage distortion at any panel or sub panel does not exceed 8 percent, and (3) that transformers and cables are sized to handle the harmonic current. It is the responsibility of the end user to provide information regarding the existing power system or the proposed power system design, and it is the responsibility of the ASD vendor or the system integrator to ensure that the above guidelines are met.

Specifying a line reactor or a DC link reactor is also an effective harmonic control specification in most of the cases. Reactors provide additional benefit of lowering line current, improving total power factor, and minimizing nuisance tripping of ASDs during voltage transients, in addition to reducing harmonic currents. The additional cost of a reactor in almost every case will ultimately result in a more robust ASD system application, greatly minimizing the impact of power quality problems.

Potential mitigation measures include:

- During installation and commissioning, the end user should request a harmonic measurement to ensure that the guidelines of the specification regarding current and voltage distortion are met after the installation of the ASD.
- If power-factor-correction capacitors are used in the facility, a before-and-after measurement of the capacitor current should be conducted to ensure that the harmonic current is not causing any resonance problem in the facility.
- Various harmonic-mitigation devices can be used for improving the input current waveform. The intent of all techniques is to make the input current more continuous so as to reduce the overall current harmonic distortion. The different techniques can be classified into four broad categories:

  1. Line reactors and/or DC link chokes
  2. Passive filters (series, shunt, and low-pass broad-band filters)
  3. Phase multiplication (12-pulse, 18-pulse rectifier systems)
  4. Active harmonic compensation

## Power Quality Problems Adversely Affecting Adjustable-Speed Drives

Like other electronic devices, ASDs are sensitive to any power quality problems, particularly in voltage supply.

### *Nuisance Tripping of Adjustable-Speed Drives Because of Overvoltage*

To protect their internal capacitor-based energy storage systems, ASDs have very sensitive overvoltage settings. The most obvious symptom of an ASD tripping because of an overvoltage is an overvoltage (OV) trip code that is displayed after the ASD trips. In most cases, OV tripping because of voltage transients affects smaller ASDs (< 20 HP) and ASDs that are lightly loaded. If the overvoltage-related trip is because of voltage transients in the input, then in most cases there will be a regular pattern—for example, the ASD trips every morning or every Monday morning. In some rare cases, components within that ASD (such as surge suppressors, DC link fuses, or input rectifiers) can be damaged.

Another common reason exists for an ASD to trip on OV, which has nothing to do with input voltage transients: energy from the load side (motor) could cause an overvoltage condition for the ASD during a braking action, where the motor energy is transferred to the DC bus. In most ASDs, these two OV-related trip codes are differentiated and the end user should verify from the user's manual regarding which type of OV is causing the drive to trip.

Mitigation measures for minimizing tripping of ASD systems because of overvoltages include:

- Specify that the ASD should be able to operate without tripping during 150 percent voltage transients for a duration of 2 milliseconds. This capability will ensure that the ASD will operate without nuisance tripping in a majority of cases. There could be instances where, because of magnification, the transients could be more severe than 150 percent.
- Another good specification is to install a line reactor or a DC link reactor to minimize nuisance tripping of an ASD during voltage transients.
- Check voltages where ASDs are connected. A higher-than-nominal voltage is more likely to cause an ASD to trip on voltage transients.
- If power-factor-correction capacitors are installed in the facility and they are suitable. Check to ensure that the switching of the capacitors will not cause the ASD to trip on overvoltage.
- Line reactors or DC link reactors are the most effective mitigation devices for minimizing nuisance tripping of ASDs because of overvoltage transients such as those caused by capacitor switching. Consult with the ASD vendor or the system integrator to determine what size of reactor will be most appropriate for the particular situation.

### *Tripping of Adjustable Speed Drives Because of Voltage Sags or Momentary Interruptions*

One ASD application concern is its sensitivity to short-duration voltage sags and momentary interruptions of the power supply. Like most electronic systems, the electronic controls that govern the behavior of ASDs are very sensitive to an interruption in power, whether in the form of a sag in voltage or in the complete interruption of power, if even for a brief time.

Whenever a fault on the transmission or distribution system serving a commercial or industrial facility exists, there will be either a voltage sag or an interruption at customer facilities. Faults cannot be completely avoided, regardless of the system design. A voltage sag will persist until a protective device clears the fault, typically in 3 to 30 cycles depending on the fault location. If the fault is on the same feeder as the facility, power is likely to be completely interrupted. With reclosing circuit breakers, power will be restored after a specified delay if the fault is temporary.

Figure 3-9 shows the voltage waveform associated with a voltage sag and Figure 3-10 shows a momentary interruption.

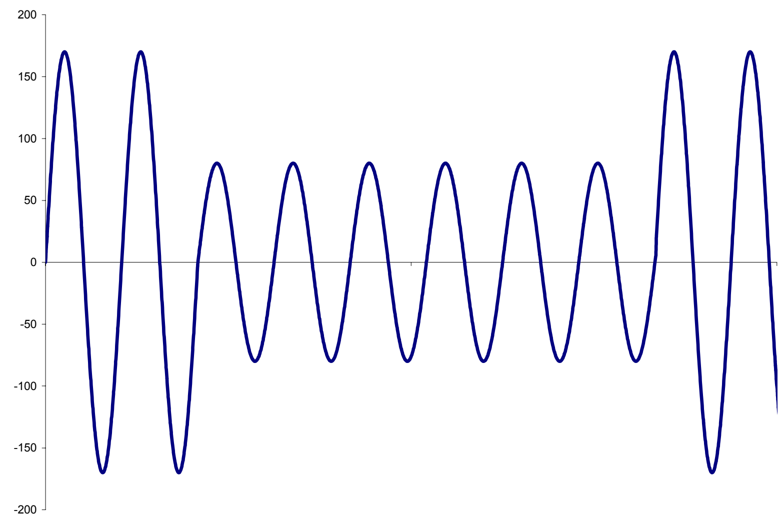



**Figure 3-9**
**Voltage Sag**


**Figure 3-10**
**Momentary Interruption**

The effect of remote system faults should be considered when ASDs are applied to critical processes. Nuisance tripping can cause an entire process to shut down. The most obvious symptom is an undervoltage (UV) trip code that is displayed after the ASD trips. These trips are often correlated with nearby thunderstorms. If the facility uses high-pressure sodium lights or metal halides lights, then these lights can also drop out because of the voltage sag that causes an ASD to trip.

There are a number of steps that appliers of ASDs can take to mitigate the impact of voltage sags and momentary interruptions on ASD-driven systems:

- Specify that at rated load, the ASD should be able to tolerate a voltage sag down to 50 percent of nominal voltage for at least 30 cycles. Under no circumstances should the ASD undervoltage trip setting be higher than 80 percent of nominal voltage.
- If the process controlled by the ASD can tolerate a speed or torque variation and if such a variation does not compromise the safety of the process or the operator, then request the ASD vendor or system integrator to evaluate the feasibility of a “flying restart” option so that the ASD can power the motor as soon as the voltage returns to normal after a sag or momentary interruption.
- Specify that the control power for the ASD should tolerate a voltage interruption for at least 2 seconds. Or, as a minimum, specify that the control power shall come from the drive’s DC link.
- For the system integrator, specify that any control circuit element that will communicate with the ASD, such as a programmable logic controller (PLC), should also have the same voltage-sag and momentary-interruption tolerance as the ASD control power (0 percent voltage for 2 seconds).
- Check voltages where ASDs are connected. A lower-than-nominal voltage is more likely to cause an ASD to trip on voltage sags.

Check to see if any small “ice cube” relays (as shown in Figure 3-11) are in the control panel of the ASDs. Ensure that the control power for the relays and other control equipment is conditioned with a UPS, constant-voltage transformer, or other device.

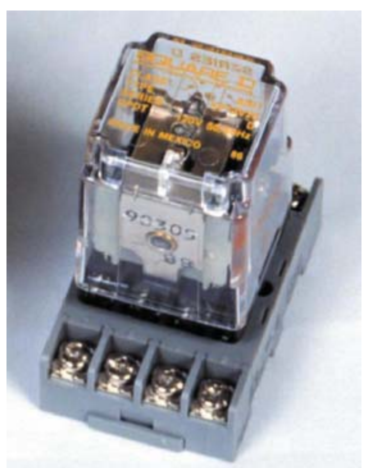


**Figure 3-11**
**Typical “Ice Cube” Relay**

- Check the proper setting of the ASD programming code that determines how the ASD should respond during and following a voltage sag or momentary interruption.

- There are several power-conditioning devices to protect control circuits for ASDs against voltage sags and monetary interruptions. The major types of ride-through devices for ASD control applications are:
    1. Uninterruptible power supply (UPS)
    2. Constant-voltage transformer (CVT)
    3. Contactor coil hold-in circuits
    4. DC bus ride-through device

       One type of voltage-sag-mitigation device for an ASD is to fortify its DC bus by either adding energy storage or installing a standby boost converter that connects directly to the DC bus. When a boost converter senses that the voltage across the DC bus is approaching the undervoltage trip point, it rectifies the remaining line voltage and boosts the DC voltage to maintain the DC bus at a level greater than the undervoltage trip point. However, boost converters require at least 40 percent remaining voltage during a voltage sag. Therefore, they cannot support the DC bus during deep three-phase voltage sags or momentary interruptions.
    5. AC bus ride-through device

       An AC bus ride-through device is similar in application to the DC bus ride-through device. However, they are used to protect the three-phase AC power instead of the DC bus. Battery-based UPS technology, which is the most common AC-side power-conditioning device, can offer protection for voltage sags and interruptions while also providing protection from longer-term outages. Several new short-term, energy-storage technologies that are currently used to protect the AC bus include flywheels and ultracapacitors. In addition to energy-storage technologies, power electronic technologies that rely on fortifying the AC bus using remaining voltage from the good phase is also available for voltage-sag protection for ASDs.

### *Tripping of Adjustable-Speed Drives Because of Current Unbalance*

Tripping of a protection circuit that senses overload or current unbalance is the main symptom of ASD tripping because of current unbalance. In rare cases, momentary voltage unbalance during single-phase sags or momentary interruptions can cause line-side fuse clearing because of excessive current drawn in one or two phases of the ASD. Presence of third-harmonic current in the line is also an indication of ASD tripping because of current unbalance. Third-harmonic current should not be present if the voltage to a three-phase ASD or any other three-phase nonlinear load is balanced. With a stiff system, such as one with a high short-circuit-current capability, a relatively small input voltage unbalance of say 2.6 percent can result in an input current unbalance of 23 to 65 percent, depending on the amount of internal inductance or reactance in the ASD. The characteristic current waveform, shown in Figure 3-12, contains high third-harmonic content as the internal series reactance saturates. This is not the normal current waveform for balanced input voltages to the ASD.

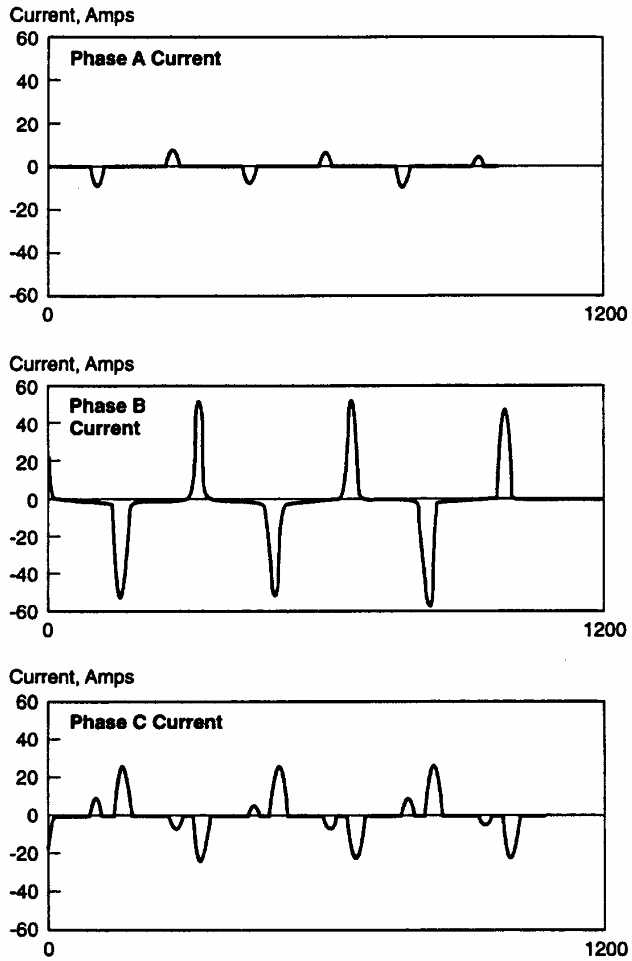



**Figure 3-12**
**High Third-Harmonic Content**

Mitigation measures to combat ASD tripping because of current unbalance include:

- Check for voltage unbalances at the panel where ASDs are connected. An unbalance higher than 2 percent will likely cause problems and require mitigation.
- If the voltage is unbalanced more than 2 percent, try to balance the line voltages by redistributing single-phase loads across all three voltage phases, relocating unbalanced loads to different power panels, and correcting all overloads within the building.
- If the voltage unbalance is traced to the service entrance and still exists when there is no load at the entrance, call your local electric utility for help.
- Do not use open delta transformer configurations; these configurations are more likely to cause excessive voltage unbalance.

Line reactors or DC link reactors help in balancing the current of an ASD when subjected to voltage unbalance.

# 4
# THE POWER QUALITY IMPACT OF ELECTRONIC LIGHTING

Like many other end-use equipment, electronic lighting systems are subject to power quality problems which arise from improper specification, improper installation, and a number of system compatibility problems resulting from these systems having to co-exist with other end-use equipment. As an introduction to these problems, the background, general design, and benefits of using electronic ballasts are discussed below.

## Benefits of Using Electronic Ballasts

The electronic ballast is rapidly becoming the standard in the lighting industry. It produces significant energy and dollar savings in nearly every application for full-sized fluorescent lamps. The electronic ballast produces light at a higher frequency and is therefore considered “flicker free” and produces virtually no noise or hum.

In addition, electronic ballasts, which significantly enhance T-8 lamp operation, provide for dimming capabilities through an integral component of any daylight-harvesting or lumen-maintenance strategy.

The most significant feature of electronic ballasts is the higher operating frequency, which is typically 20 kHz to more than 100 kHz. Standard electromagnetic ballasts use 60 Hz. Thus, electronic ballasts can convert power to light more efficiently and consume less power.

For example, an electronic ballast operating two 4-foot energy-saving lamps requires an input power of 60 W compared to 82 W of input power on a conventional electromagnetic ballast. This amounts to a 27 percent energy savings.

Not only do you get a better power factor and higher luminous efficiency with electronic ballasts, but also the instantaneous starting time cuts down on eyestrain. According to industry experts, the average incidence of headaches and eyestrain in offices was cut more than one-half under higher frequency lighting.

Other benefits of electronic ballasts include a higher life expectancy, a reduction in noise level, and a lower operating temperature, which results in more energy saving in air-conditioning requirements as well as lower potential maintenance.

### How Electronic Lighting Works

Electronic ballasts control a high-frequency lamp voltage and current using electronic circuits. In the past, all electronic ballasts rectify the incoming 60-Hz power and convert it to high-frequency energy in the range of 20 kHz to 150 kHz. Some of the more mature electronic ballasts using radio-frequency plasma generator technologies are generating high-frequency energy in the 2 MHz to 20 MHz range.

This high frequency excites the phosphors in a fluorescent lamp more efficiently than the energy from the standard 60-Hz frequency, providing more light output for the same amount of energy consumption. Ballast losses are also generally lower for electronic ballasts than for magnetic ballasts. Other advantages of the electronic ballast include reduced weight and reduced audible noise. Reduced sensitivity to fluctuations of the line voltage that is known to cause flicker in lamps may also be an advantage in some models. In most instances, electronic ballasts are manufactured in standard ballast casings to allow direct replacement in existing luminaries during lamp-ballast retrofit programs.

A simplified block diagram of a typical electronic ballast is shown in Figure 4-1. A full wave bridge rectifier is normally used to change the incoming AC voltage to DC. The large storage capacitor provides the necessary DC link voltage for the inverter. The inverter, which produces a high-frequency output normally in the range of 20 kHz to 100 kHz, can be characterized by the circuit topology and the inverter-control method. The high-frequency transformer serves as a network-matching device that matches the output impedance of the inverter to the input impedance of the lamp (which may be positive or negative—depending on the operating conditions of the lamp). Some electronic ballasts use inductors and capacitors to achieve the necessary matching. Some newer designs include control wiring to achieve dimming and other control functions. The introduction of these features further complicates power quality problems in that the ballast has additional ports for unwanted energy to enter.

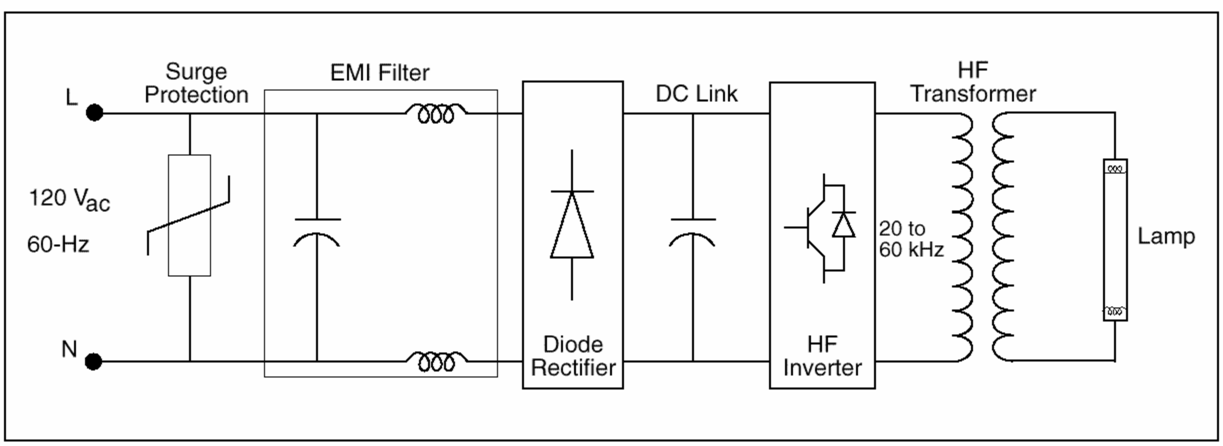



**Figure 4-1**
**Basic Design Structure for an Electronic Ballast**

## Power Quality Problems Caused By Electronic Lighting

A number of compatibility problems have occurred in the field as a result of installing electronic ballasts without understanding how to avoid such problems. Examples of the problems that have occurred include:

- High total harmonic distortion (THD) in the line current on lighting panels
- Early failure of ballasts and lamps
- Early failure of occupancy sensors
- Malfunctions of energy management systems
- Malfunctions of centralized clock systems
- Malfunctions of infra-red (IR)-based consumer electronic devices
- Malfunctions of personal electronic devices such as a hearing aid

### *Total Harmonic Distortion from Electronic Lighting*

When electronic high-frequency ballasts were first introduced in the early 1980s, some models generated relatively high line harmonics. Nevertheless, at that time, harmonic currents produced by lighting equipment and other electronic systems were not, as yet, a utility issue. However, by the mid-1980s, utilities and power engineers were becoming increasingly more concerned about power equipment that generated line harmonics.

The harmonics issue first surfaced as a concern to the professional lighting community when a major utility announced that electronic ballasts were required to have total harmonic distortion (THD) of less than 20 percent of the fundamental to qualify for their rebate program. Electronic ballast manufacturers responded to the utility's requirement by employing passive filtering that met the 20 percent limit at a slightly higher cost to the end user.

End users should be aware of reports of harmonic distortion from electronic ballasts. However, few severe electrical problems have been reported because of THD problems (caused by the installation of electronic ballasts).

The installation of electronic ballasts will generally reduce the overall load on a circuit by reducing energy demand. All of the major ballast manufacturers produce products that are less than 20 percent THD, and less than 10 percent THD ballasts are available for a premium cost. The standard magnetic ballasts that have been replaced by electronic ballasts usually have a THD of 25 percent or greater. These magnetic ballasts also consume on the average 2 W to 6 W more energy that their electronic replacements.

### *Electromagnetic Interference Problems From Electronic Lighting*

Electromagnetic interference (EMI) is not a new problem. In fact, EMI problems have been occurring long before power quality problems were even thought of. To many electrical experts, EMI problems are a subset of power quality problems. In many cases, it is only the frequency, shape, and cause of the disturbance that separates the two. Some background discussion of EMI and EMI problems as they relate to electronic lighting are discussed below.

Electromagnetic energy of various wavelengths and frequencies make up the electromagnetic spectrum. The spectrum includes all forms of radiant energy: x-rays, gamma rays, infrared radiation, light, ultraviolet radiation, and television and radio waves. EMI occurs when electromagnetic waves affect the performance of end-use equipment such as an energy management system or medical device.

A poorly shielded power supply, poor wiring layout, or improper grounding may allow the transmission of electromagnetic energy. The operation of electronic ballasts produce radiated and conducted emissions as a byproduct. End-use equipment may generate currents and voltages as an intended part of their design (for example, recording information on magnetic tape). In the case of EMI, these currents and voltages may contain undesirable artifacts of the device's design or installation, which cause it to malfunction.

EMI can take two forms: conducted or radiated. Conducted EMI occurs when electronic devices induce currents in the building wiring system that adversely affect an electronic device on the same system. Radiated EMI is associated with radiated energy, for example, energy in the form of electric and magnetic fields inherent in electronic devices.

### Determining if Electromagnetic Interference Is Emanating from a Lighting System

A specifier who suspects that EMI is affecting the performance of a piece of equipment can identify the source using the following procedure. First, turn off all the luminaries and all the electrical equipment in the room except the affected equipment. The malfunctions should cease if the lighting system or any of the other electrical equipment is the cause of the EMI. Next, turn the luminaries back on, one at a time if possible, while checking the functions of the affected equipment. If the malfunctions reoccur when a luminary is turned on, that luminary is probably the source of the EMI. Users should also check the compatibility of the affected equipment with other devices in the space by turning them on one at a time and checking the functions of the affected equipment.

### Potential Electromagnetic Interference Problems with Electronic Lighting Systems

Table 4-1 lists examples of products susceptible to EMI, potential problems, and possible solutions that the installer or end user can implement if a fluorescent lighting system is involved in an EMI problem. The methods used to minimize EMI from high-frequency fluorescent lighting systems depend on the susceptibility of the end-use equipment and whether the EMI is conducted or radiated. Specific solutions to specific problems depend on the application, but Table 4-1 lists examples of EMI involving fluorescent lighting systems and possible solutions.

**Table 4-1**
**List of Electromagnetic Interference Problems Associated with Electronic Lighting, Causes, and Possible Solutions**

| Affected End-Use Product | Compatibility Problem | Cause | Possible Solutions |
|---|---|---|---|
| Article Surveillance Systems (anti-theft tag detection) | System fails to detect charged strip in product passing through detector at exit doors. | Magnetic fields emanate from electronic lighting system within 10 to 20 ft of system. | 1. Add emissions filter to theft detection system.<br>2. Replace electronic ballasts that are within 10 to 20 ft of system with magnetic ballasts.<br>3. Replace analog detection system with a digital detection system. |
| Control devices that use communication wiring (for example, occupancy sensors, photo-sensors, programmable thermostats) | Controls do not respond correctly to settings. | Integrity of low-voltage signals on the control wiring is altered by emissions from electronic lighting system before control signal reaches its destination. | 1. Maintain 3 ft separation distance between low- and high-voltage wiring.<br>2. Use twisted-pair wire for low-voltage wiring.<br>3. Ground lighting fixture.<br>4. Rearrange ballast output wiring in fixture.<br>5. Add filter to control device.<br>6. Use magnetic ballasts in vicinity of control devices.<br>7. Shield fluorescent lamps with prismatic lenses containing shielding screen. |
| Cordless and cellular phones | Static or screeching sounds. | Desired phone signal distorted by emissions from electronic lighting systems. | 1. Change phone channel.<br>2. Move away from lighting systems. |
| Infrared (IR) -based remote controls on consumer electronic devices (for example, TVs, VCRs, stereos, cable TV converters, wireless headsets) | IR receiver does not respond to remote control, device responds erratically (rapid turning on and off, volume changes, channel changes). | IR emissions from high-frequency fluorescent lamps interact with remote control IR or saturate IR receiver on device. | 1. Rearrange layout of room such that different line-of-sight is established between lighting systems and devices.<br>2. Use incandescent lamps or magnetic ballasts near devices.<br>3. Install special IR filter over IR receiver of device. |

Table 4-1 Continued

| Affected End-Use Product | Compatibility Problem | Cause | Possible Solutions |
|---|---|---|---|
| Intercoms (power-line carrier based) | Static or screeching sounds. | Conducted emissions from electronic lighting systems distort power-line carrier signal flowing on building wiring system. | 1. Add a filter to the intercom.<br>2. Change intercom channels when possible. |
| Energy-management systems (EMS) (power-line carrier based) | Controls do not respond, controls respond erratically without command. | Harmonic current filters on the input of electronic ballasts attenuate ("signal-sucking" power-line carrier signal; conducted emissions from ballast simulate carrier signal. | 1. Strategically place a filter in the building wiring system to prevent emissions and interaction of ballasts with EMS.<br>2. Use different electronic ballasts.<br>3. Use magnetic ballasts.<br>4. Change EMSs. |
| Centralized clock systems (power-line carrier based) | Clocks do not respond to time synchronization signal, clocks slow or advance too quickly. | Harmonic current filters on the input of electronic ballasts attenuate ("signal-sucking" power-line carrier signal; conducted emissions from ballast simulate carrier signal. | 1. Strategically place a filter in the building wiring system to prevent emissions and interaction of ballasts with clock generator.<br>2. Use different electronic ballasts.<br>3. Use magnetic ballasts.<br>4. Change clock generator frequency.<br>5. Separate clock system wiring from lighting system wiring. |
| Electronic medical equipment (for example, EKG, EEG, EMG machines) | Errors in patient data, unusual machine responses, lost patient data, corrupt patient data. | Radiated and/or conducted emissions from electronic lighting systems interact with patient leads of medical devices or power line cord. | 1. Ground lighting fixture.<br>2. Rearrange ballast output wiring in fixture<br>3. Add special and approved filter to medical device.<br>4. Use magnetic ballasts in vicinity of control devices.<br>5. Shield fluorescent lamps with prismatic lenses containing shielding screen. |

Most of the solutions described in Table 4-1 require electrical wiring changes, except for shielding and moving the equipment from one location to another. However, lamp shielding warrants a special explanation. A prismatic lens containing conductive mesh molded within can be placed inside a luminary to block electromagnetic energy that originates in fluorescent lamps. The incident electromagnetic energy induces a current in the conductive mesh. That current in turn induces an opposite electromagnetic energy, which negates the effect of the incident energy.

Although the mesh material reduces the electromagnetic energy from the lamp, it also reduces light transmission from the luminary's lens. Specifiers should consult product literature for information regarding the percentage of light lost because of the mesh. Effective shielding material may reduce light transmission by more than 20 percent, so specifiers may want to install additional luminaries to compensate or consider alternatives to shielding.

# 5
# EVALUATING THE ENERGY-SAVING POTENTIAL FROM NON-TRADITIONAL MEASURES

## Transient Voltage Surge Suppressor

Transient voltage surge suppressor (TVSS) technologies (also known as a surge protective devices, or SPD) are connected to a building wiring system and used to clamp, divert, or absorb most of the transient energy associated with spikes or surges in voltage, whether from a lightning strike or other source. The primary function of a surge-protective device is to protect sensitive load equipment against the damaging effects of a voltage surge.

Transient overvoltages can cause breakdown of insulation, resulting in either a temporary disturbance of device operation or instantaneous failure. The insulating level in the former case will be weakened leading to premature failure. The severity of the breakdown varies with the type of insulation—air, liquid, or solid. The first two tend to be self-healing, while breakdown of solid insulation (generally organic materials) is a permanent condition. Therefore, a significant potential benefit of using TVSS technology is that the lifetime of protected devices may be extended because insulation breakdown and subsequent device failure can be avoided.

In typical AC-powered equipment, the sensitive components are powered line-to-neutral in single-phase 120-V systems, or line-to-line in three-phase systems, and that is where the TVSS is installed. There is usually no need for any protection from line-to-ground. The line-to-ground withstand capability of equipment is only an insulation concern, typically addressed by equipment standards and requiring levels much higher than the levels of concern in line-to-neutral surge events affecting electronic components or clearances of circuit traces.

Typical components inside the TVSS may include metal oxide varistors (MOVs), gas tubes (spark gap), and avalanche diodes (see Figure 5-1). The TVSS is an excellent device to aid in the protection of equipment from high-voltage, short-duration transients lasting less than 1 millisecond. These products typically do not provide any other power conditioning actions such as sag or swell protection or harmonics mitigation.

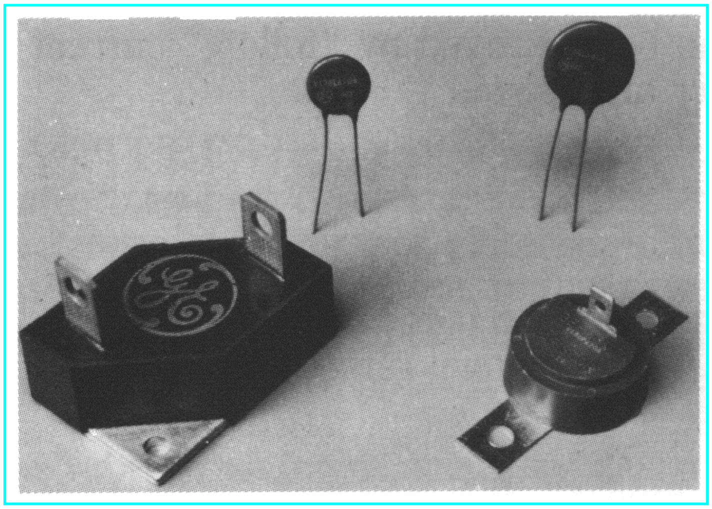


**Figure 5-1**
**Metal Oxide Varistors (MOV) Handle Most Transients Occurring Inside a Facility**

In the low-voltage (end user) environment, surge-protection schemes act by diverting impinging surges by offering a low-impedance path to return the surge current to its source, or by restricting the propagation of surges between their point of origin and the equipment to be protected. This function can be accomplished in one or several stages, depending on the system configuration and the degree of freedom available to the users for connecting protective devices at different points of their systems.

In its simplest form, the diversion can be obtained by a device connected across the line, hence the generic description “shunt-type SPD”. In a more complex form, surge protection is obtained in several stages by combining diversion and restriction, such as that shown in Figure 5-2. This approach, which uses restriction combined with diversion places great emphasis on a restriction performed by an inductor connected in series with the line, hence the generic designation of “series-type SPD.”

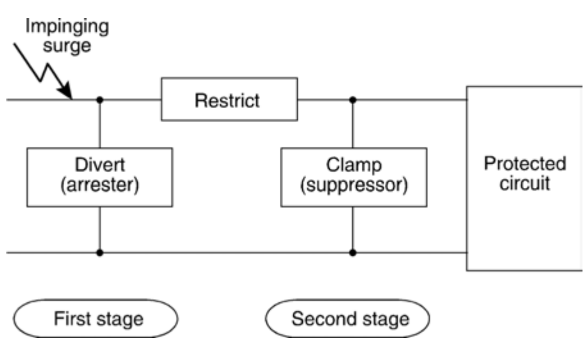



**Figure 5-2**
**Basic Approach to Multi-Stage Surge Protection**

As shown in Figure 5-2, the first stage provides diversion of impinging high-energy surges through a high-energy handling device, sometimes called “arrester,” which is typically installed at the service entrance, or by a device permanently connected at the service panel. Some restriction to the propagation of surge currents in branch circuits is inherently provided by the inductance of the premises wiring, or by insertion of a discrete inductor. The second stage of voltage limiting is provided by a SPD of lesser surge-handling capability, often called "surge suppressor" or "surge protector," which is typically located close to the equipment in need of protection as an add-on, plug-in device or incorporated within the equipment by the manufacturer. This second stage completes the scheme for surges of external origin as well as for surges originating within the building.

## *Understanding Transient Voltage Surge Suppressors*

Important parameters for the selection and operation of TVSS devices include:

### Let-Through Voltage

The let-through voltage (LTV) specification (sometimes referred to as the clamping voltage) refers to the lightning and surge-suppression capability of the power-protection device. The two issues of interest are first, did the protection device survive the transient, and secondly, what percentage of the voltage transient was "let-through" to the load? Most plug-in and panel-mount TVSS manufacturers will claim ability to survive and attenuate a "6-kV Category A or B transient" as described in ANSI/IEEE C62.41. The remaining peak voltage (after attenuation) from the 6-kV shot is referred to as the LTV and will typically be specified for all applicable conductor combinations (L-L, L-N, L-G and N-G as applicable). The manufacturer may also have a UL1449 listing and the LTV for each conductor combination will be given.

### Maximum Surge Current

This "one-time, one-shot" specification is important to the user because it describes the ability of the surge-protective device to shunt transient surge current and the corresponding one-half cycle short-circuit current of the power system without opening up or catastrophically failing. The one-shot rating for maximum surge current varies substantially from manufacturer to manufacturer but is generally derived from the specification sheet for the protection device (either the MOV, the gas tube, the avalanche diode, or other suppression device used).

Confusion with this specification is caused because manufacturers may have six or more individual suppression devices inside of their product and may (or may not) add up the one-shot values for all of the devices to derive their maximum surge current specification. *It is prudent for the specifier to request a more detailed breakdown from the manufacturer on how the maximum surge current rating was derived.*

### Metal-Oxide Varistors

Metal-oxide varistors (MOVs) are made of sintered metal oxides, primarily zinc oxide with suitable additives. When subjected to high-voltage transients, the varistor impedance changes from a near open circuit to a near short circuit. Potentially destructive energy of a voltage transient is clamped and the surge current diverted or “shunted” away from the protected equipment by a varistor. Once the event is over, the MOV goes back to its normal, open-circuit, high-impedance mode of operation.

### Maximum Continuous Operating Voltage Rating

Maximum continuous operating voltage (MCOV) is the maximum, steady state, sinusoidal, root-mean-square (RMS) voltage that may be applied to a varistor without reducing varistor life expectancy. The higher the MCOV rating of the MOV, the higher is the clamping voltage. Note that while lower clamping levels imply better load protection, the closer the MCOV comes to the actual applied voltage, the shorter the life expectancy of the TVSS product. A good rule of thumb is to look for an MCOV at least 10 percent higher than the expected RMS voltage of the circuit because variances occur in the actual utilization voltage supplied on any given utility distribution system.

### Thermal Fuse

A thermal fuse is a reliable thermal cutoff designed to protect from fire. Operation of the fuse opens an electrical circuit when the temperature of the fuse increases to an abnormal level. A typical fuse contains a sliding contact, springs, and a thermal pellet inside a metal case. At normal temperature, current flows through the fuse. When the temperature near the fuse rises to unsafe levels, heat is transferred through the metal case of the fuse and melts the thermal pellet. The melted thermal pellet allows the springs to expand, which moves the contacts apart breaking the electrical circuit.

A thermal fuse protects against a surge suppressor catching fire because of a failed MOV. MOVs may fail because of old age, excessive transient exposure, or if the rated RMS voltage is exceeded for an extended period of time. A failed MOV may, under certain conditions, heat up if the upstream fuse does not open. A thermal fuse, by detecting the increase in temperature, breaks the electrical circuit, preventing the buildup of heat in the failed MOV.

The purchaser of TVSS equipment should insist that the equipment have a thermal fuse. Position of the thermal fuse with respect to *all* MOVs is critical. Placing a thermal fuse within a few millimeters of the MOV shell should protect every MOV connected to a hot conductor. The second edition of UL 1449-1996 defines and specifies tests for various MOV failure modes. When purchasing TVSS equipment, ensure it meets UL 1449, second edition.

### Energy-Handling (Joule) Rating

Joule (J) ratings for TVSS devices have become a game of specmanship in the industry and it is highly advisable to avoid using the joule rating to attempt comparison of products or to try to determine the quality of protection.

### *Energy-Saving Potential of Transient Voltage Surge Suppressors*

In recent years, a handful of TVSS products have been marketed not only as protection from lightning strikes and other overvoltage events, but also as energy-saving tools, and claiming rapid economic payback of investment. The assumptions behind such claims is usually as follows:

- Overvoltage events are common and occur often in most facilities
- These overvoltage events cause end user equipment to run hotter than normal
- Equipment operating at higher temperatures is less energy efficient than the same equipment operating at lower temperatures
- Installation of the manufacturer's TVSS technology isolates equipment from these overvoltages, thereby preventing heat buildup and improving energy efficiency
- The manufacturer's TVSS technology is cost effective when compared to alternative approaches, either for overvoltage protection or for enabling cooler equipment operation

To justify the purchase of TVSS technology for the purposes of improvements in energy efficiency at a particular facility, each and every one of the above assumptions must be substantiated for that facility—a very difficult task.

There has been considerable and ongoing public debate within the electric power and power quality industry over the energy-saving capability of TVSS for energy-saving devices. This debate has been driven by a general lack of evidence in technical literature to substantiate the assumptions listed above.

Some recent research has found evidence that energy consumption of electrical devices is not appreciably increased by the presence of transient voltages. As an example, consider a 120-V, single-phase line with a 20-Ω load and a 50-Ω source impedance. A lightning transient of 6-kV peak, 5-μs duration will deliver approximately 0.4 J to the load. A switching transient of 6-kV peak, 8/20 μs waveshape will deliver approximately 2 J to the same load. Based on survey data, extreme exposure to high-voltage transients may be approximately 80 events per year. At that rate, the lightning transients would deliver approximately 32 J or 0.009 Wh to the 20-Ω load in a year. So, the total energy in these transients is extremely small. In fact, the average energy even in severe transients is so small that it will neither produce discernible heating in load equipment, nor appear on a watt-hour meter.

## Power-Factor-Correction Capacitors

Power factor is the ratio of two measures of electric power: *real power* [measured in kilowatts (kW) and what end users normally pay for] and *apparent power* [measured in kilovolt-amperes (kVA) and representing the total amount of generation and distribution capacity an electric utility must provide to meet the needs of the load]. The difference between the two (calculated vectorally) is call *reactive power*, and is measured in kiloVARs (kVAR). In general, it is more expensive for an electric utility to provide power to an end user facility that has poor power factor than it is to provide the same level of service to a neighboring plant with good power factor. As a result of the power-factor effect, utilities and end users react in two ways:

1. Utilities charge "power factor penalties" for end users with poor power factor

2. Utilities or the end users install power-factor-correcting capacitors to achieve improved power factor and thus reduce the kVARs a facility draws from the electric utility

Utilities and their commercial and industrial customers use shunt-connected capacitors to correct lagging power factor. Lagging power factor is primarily caused by induction motors, thyristor-based motor drives, transformers, and other inductive loads. Shunt-connected capacitors provide the reactive power that is required by inductive loads. Their relatively low cost, ease of installation, low maintenance, and very low losses make capacitors an attractive choice for power-factor correction. Capacitors may also provide four application benefits: (1) avoidance of power-factor penalties, (2) release of electrical system capacity and voltage regulation improvement, (3) reduction of electrical system losses, and (4) energy savings.

### *Capacitor Benefit #1: Avoidance of Power-Factor Penalties*

Some utilities charge their industrial and commercial customers based on the system capacity (kVA) required to serve the customer's facility. There are a number of utility customers that have a large number of inductive loads within their facilities (such as induction motors and transformers). These loads may draw substantial reactive power from the utility supply.

Low power factor means the utility must supply a customer that has a higher apparent power (kVA) demand relative to the real power (kW) demand. This causes an increase in the distribution and transmission system current levels without an increase in the energy (kWh) sold to the customer. Thus, the utility cannot serve as many customers as it could if the apparent power (kVA) demand were lower because the total current in the distribution and transmission feeders is the limiting factor.

By charging for the apparent power (also known as a power-factor penalty), the utility gives their customers an incentive for correcting for lagging power factor. A capacitor bank installed on the customer's side of the meter corrects the power factor and reduces the apparent-power demand from the utility to serve the customer. Thus, the customer's purchased-power bill will be lower than if power-factor-correction capacitors were not installed.

### *Capacitor Benefit #2: Release of Electrical System Capacity and Voltage Regulation Improvement*

Utilities practice the same principles as their customers when they install shunt capacitor banks. The capacitors provide the reactive power required by the power system (including customer loads). The cumulative effects of several customers with low power factors can significantly increase the apparent power load on the system. Installing capacitor banks allows the utility to increase the number of customers that can be serviced through their existing distribution and transmission systems.

The same principles hold true inside the customer's own facility. Lowering the apparent power required to service loads within the facility frees up capacity to expand and service new loads without the need to increase the current capacity of the existing electrical infrastructure.

Capacitors also have the added benefit of improving voltage regulation throughout the power system. Utilities install capacitors at specific locations within the system to increase the voltage at a specific point in the power system. The reactive support provided by the capacitors helps to reduce voltage drop. Lowering of the apparent power reduces system current levels and reduces system voltage drop. Capacitors installed within a customer's facility also have the same effect. However, in industrial and commercial facilities, the installation of capacitors is not usually justifiable on the basis of system voltage rise alone.

### *Capacitor Benefit #3: Reduction of Electrical System Losses*

The lowering of electrical system losses and the increase of system efficiency through the use of shunt capacitor banks is primarily the result of lower conductor losses. The real power (kW) losses in an electrical conductor are a function of the current flowing through the conductor and the resistance of the conductor. The conductor losses are directly proportional to the square of the current flowing through the conductor ($P_{loss} = I^2R$). Lowering the apparent power demand of the load will decrease the current flowing through the power conductors that service a load, resulting in a lower real power demand from the power system.

### *Capacitor Benefit #4: Potential Energy Savings*

By reducing reactive current, capacitors have the potential to provide modest energy savings in facility wiring systems. To achieve these savings, capacitors must be installed as close as possible to loads with low power factor. Based on the system power factor before and after the installation of power-factor-correcting-capacitors, Equation 5-1 shows the formula for computing the percent reduction in real power losses for a given system.

$$\textbf{\% Loss Reduction} = 100\left[1-\left(\frac{pf_{old}}{pf_{new}}\right)^2\right] \quad \textbf{Equation 5-1}$$

For example, with an old power factor of 0.7 and a new power factor of 0.9, the system losses due to reactive current can be reduced by nearly 40 percent. While this may seem a large percent savings, the absolute amount of energy saved depends on how much energy was lost in facility wiring to begin with. Figure 5-3 shows the reduction in system losses the capacitors provided the power system supplying this motor. Please note that the values in Figure 5-3 are based on percentages and not on the real power (kW) savings. To accurately assess the real power or kW savings, actual values of system resistance and current measurements taken before and after the application of the capacitors would be required.

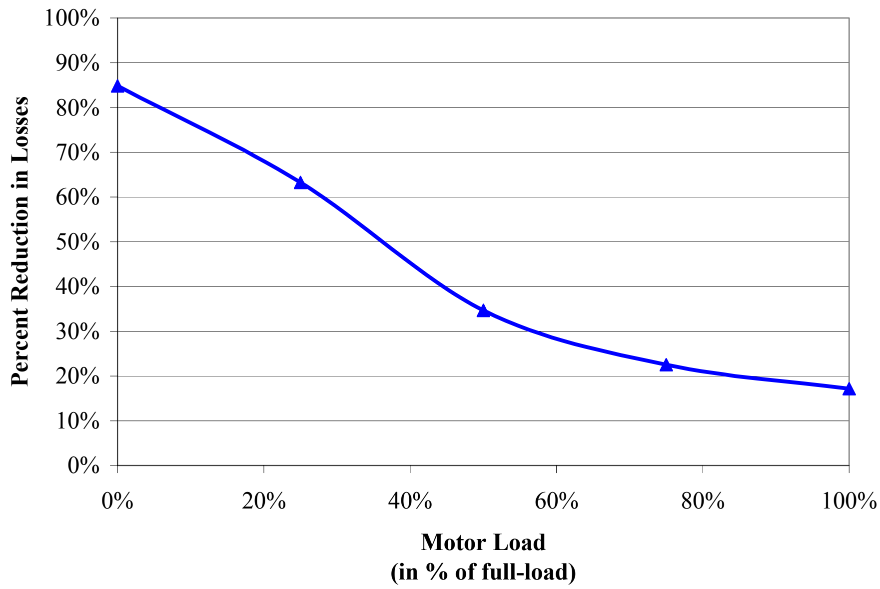



**Figure 5-3**
**Percent Reduction in Infrastructure Power Losses for a Motor *With* Shunt-Connected Capacitors Installed**

Typically, in an industrial or commercial facility, energy losses because of $I^2R$ heating in intra-facility conductors are, at most, 1-2 percent of total facility load. **Error! Reference source not found.** shows the loss reduction as a percent of total facility load for power factor improvement (at the load) from original 0.6 to 0.7, 0.8, 0.9, and 0.95. The figure is based on the assumption that system losses attributable to reduced power factor are 2 percent of total facility load and the power factor improvement scheme is implemented at the load to gain maximum advantage of loss reduction. For most facilities, overall energy savings of more than 0.5 percent from power factor would be a significant accomplishment.

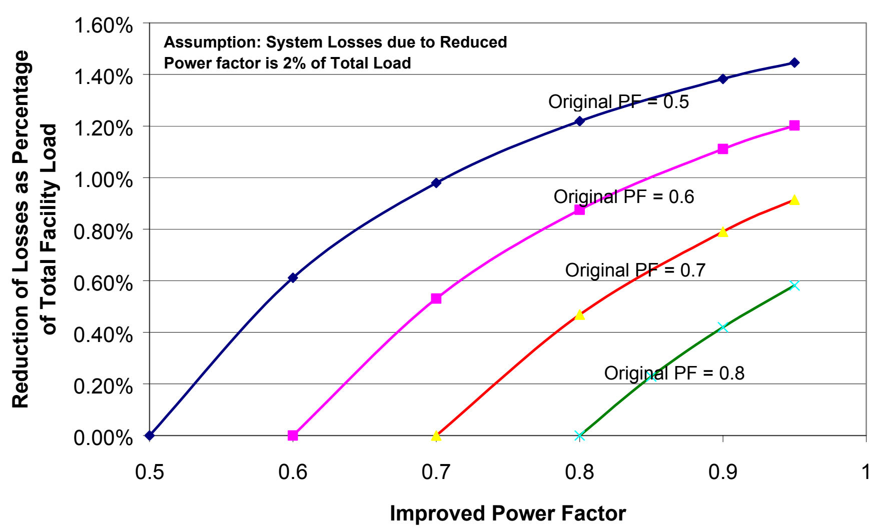



**Figure 5-4**
**Impact of Power-Factor-Correcting Capacitors on Total Facility Load**

## Harmonic Filters

Harmonics are unwanted frequencies in electrical voltage or current other that the normal, 60-Hz fundamental. These frequencies are typically between 180-Hz and 3,000-Hz. While harmonic voltages are considered to be much more injurious to sensitive equipment than current harmonics, reducing or controlling voltage harmonics almost always involves first reducing harmonic currents. One important tool to accomplish this is the harmonic filter.

Whereas power-factor-correcting capacitors are designed to reduce reactive current, harmonic filters are used to mitigate the injection of harmonic currents at higher frequencies than the fundamental 60-Hz. Most harmonic currents in commercial and industrial systems are caused by nonlinear loads (that is, loads that draw currents whose frequencies differ from the frequency of the source). Many electronic devices are nonlinear loads because they use solid-state rectifiers at their inputs and filter capacitors after the rectifiers.

Solid-state rectifiers inherently draw current in pulses, when the AC line voltage is higher than the voltage across the filter capacitor used with the rectifier. This pulsed current is very rich in harmonics, as seen in Figure 5-5. The harmonic spectrum shows the presence of odd harmonics, with relatively large magnitudes at the lower frequencies. As the frequency increases, the magnitudes decrease.

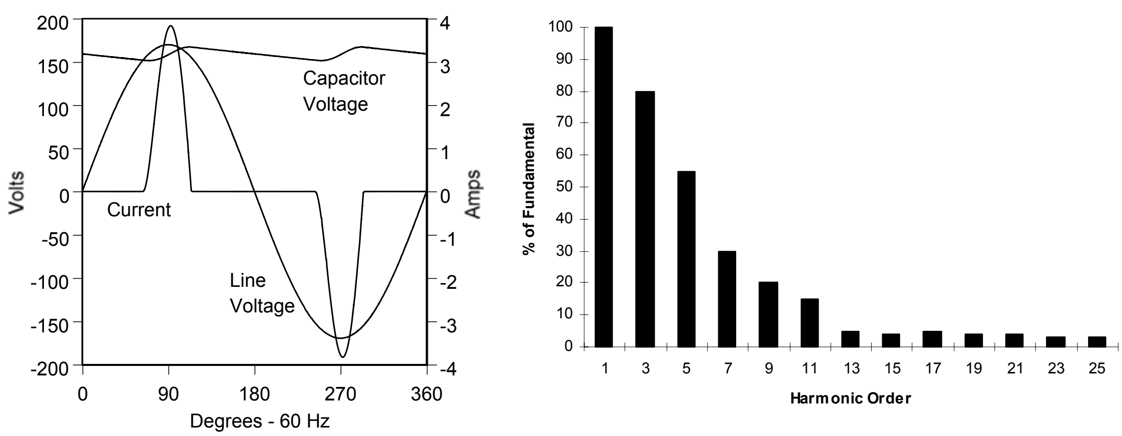



**Figure 5-5**
**Pulsed-Current Power Supply – Current and Spectrum**

The pulsed-current power supply is only one of many possible harmonic producers in the 120-V range. Other loads that inject harmonic currents include, (1) office equipment for communications, printing, and copying and (2) lighting with high efficiency electronic ballasts. Nonlinear loads in the 480-V range include adjustable speed drives (ASDs) for HVAC, larger computers, uninterruptible power supplies, and 277-V lighting.

Traditionally, harmonic filters have been passive (that is, using only simple, non-intelligent inductors and capacitors connected in various arrangements to achieve attenuation of currents of specific frequencies). These filters require tuning to the frequency of interest. Once tuned, they are restricted to operate on that band of frequencies. If multiple frequencies require mitigation, then additional stages of filtering are also required. These stages can be tuned independently of each other and cascaded together, but are still passive in the sense that they cannot adapt or change with system requirements. Passive filters must be designed with fundamental frequency, reactive compensation in mind and also present the possibility of creating or changing system resonances. An example of the application and effectiveness of a typical harmonic filter is shown in Figure 5-6.

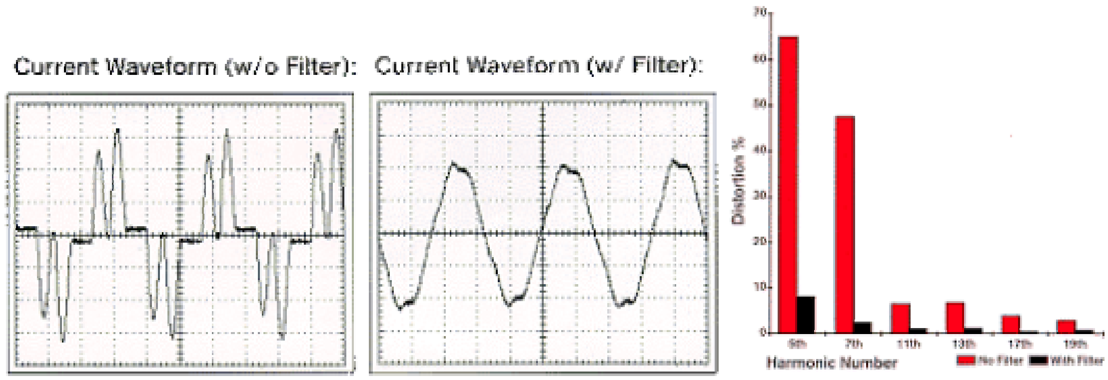



**Figure 5-6**
**Current Waveforms and Distortion Spectrum With and Without a Broad-Band Harmonic Filter**

### *Energy Saving With Harmonic Filters*

As with power-factor-correcting capacitors, the main energy savings feature of harmonic filters involves the reduction of the line current, and thus the reduction of the $I^2R$ losses in intra-facility electrical conductors. The energy saving potential of these devices will depend, naturally, on the level of harmonic currents that exist with a facility, and the degree of heating these currents are causing. Various studies have found that overall facility energy savings for a properly designed, passive harmonic filter system may be as little as a few percentage points. It should be noted, however, that based on wiring loss reduction alone, few if any harmonic filter options can pay for themselves within their expected life span.

## Electric Motor Voltage Controllers

Power/energy-saving motor controllers are widely available under a variety of trade names. These devices are often called power-factor controllers (PFC), torque controllers, energy savers, motor voltage controller (MVC), and sundry other monikers. What they actually do is control the amplitude of the voltage applied to a motor. Virtually all of these devices are variations on the basic concept invented and patented by NASA engineer F. J. Nola in the mid and late 1970s. Nola-type controllers use feedback control of solid-state switching devices at the motor terminals to modulate and change the effective input or drive voltage of a motor as the mechanical load on the motor shaft rises or falls.

Because a motor is designed to be able to deliver its full-rated output power at its normal level of terminal voltage (for example, 120-V for single-phase motors), the situation of full terminal voltage but reduced load leads to an excess of magnetic excitation within the motor structure (that is, more magnetic excitation than what is need to do the job of driving the motor at its reduced level of output). This excess excitation leads to an excess motor loss component that can be avoided by simply lowering the motor excitation (that is, lowering the terminal voltage). A lowering of the motor voltage will tend to lower the motor magnetic excitation loss, both in the motor iron (which then carries lower motor magnetic flux) and in the motor windings (which then conduct lower total current because of the lower required level of magnetic flux production). If the motor can still drive the reduced load at the reduced voltage level, then depending on the particular design of the motor, the motor efficiency should be increased over that of the case of the same motor driving the same reduced load but at full motor voltage.

The theory of operation of a MVC device is simple. Motors used in appliances are designed to deliver full power at a terminal voltage of approximately 115-V RMS. However, when a motor is less than fully loaded, applying a rated terminal voltage produces more magnetizing current than is required to drive the load. MVCs are designed to reduce the power consumption of a motor by reducing the RMS voltage when the motor load decreases, thus reducing the core losses associated with the excess magnetizing current. Figure 5-7 shows the output of a typical MVC connected to a motor loaded at 25 percent of its rating. Note the notches in the output voltage, which result in a reduction in RMS voltage of the MVC output compared to its input.

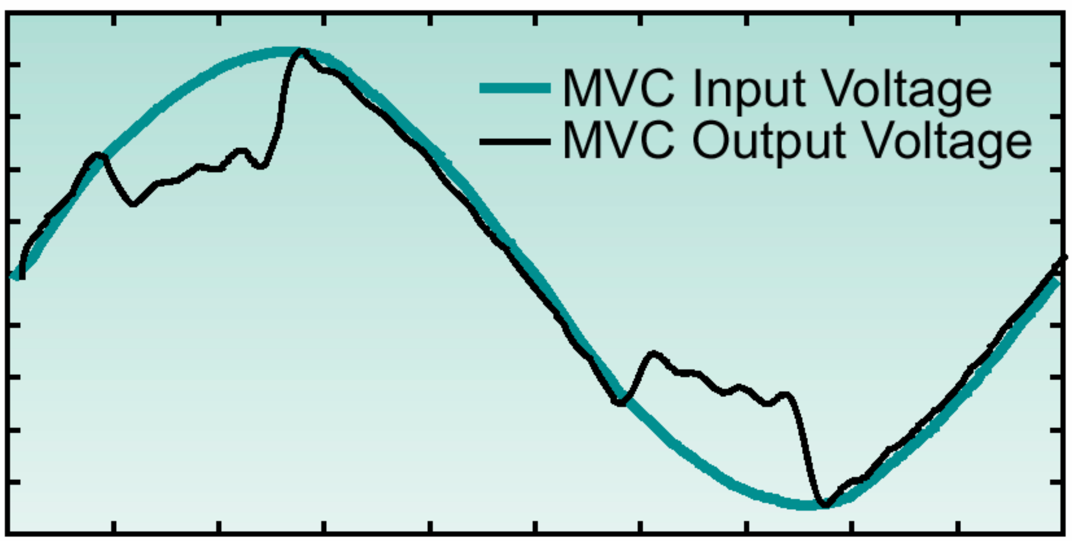



**Figure 5-7**
**Input and Output Voltages of a Typical Motor Voltage Controller**

The application of MVCs is ideal for older, low-efficiency appliance motors. However, today's appliance motors are energy-efficient, and many run at full load so that an MVC may not achieve its purpose and in fact may be counterproductive. Additionally, because MVCs are nonlinear devices, one concern of electric utilities is how much harmonic distortion MVCs contribute to the electrical system and does such a contribution offset any savings in power consumption.

### *Saving Energy with Motor Voltage Controllers*

The trick with the application of MVCs is not saving energy but, rather, in saving enough energy with the devices to justify their cost and added complexity to the motor system. As shown in Figure 5-8, the lighter the load on an induction motor, the more opportunity MVC devices have to save energy. However, significant savings (as a percentage) occur only at very low loads, and therein lies the problem: saving a high percentage of a small number yields a small number. For example, with a 1-HP motor operating at 25 percent load (or 0.25 HP), addition of an MVC device might improve efficiency from 30 percent before to 36 percent afterwards, a 20 percent improvement. However, because of the light loading of the motor, the actual energy saved is approximately 1/8-HP—a level that will require extended operation of the motor at this light loading to pay for the MVC device.

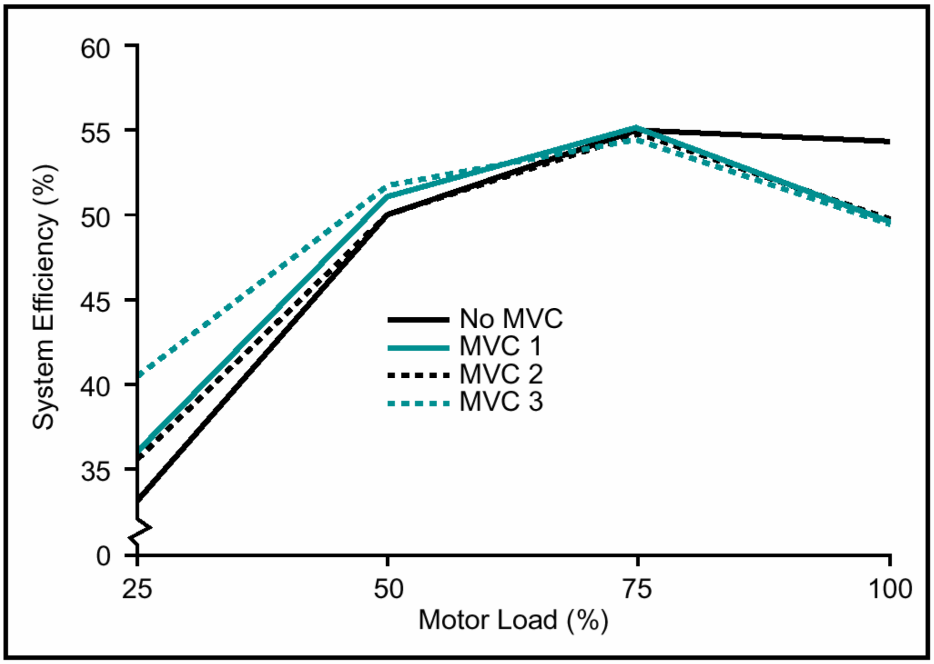



**Figure 5-8**
**System Efficiency at Different Motor Loads with Different Motor Voltage Controllers**

## Electric Motor Soft Starters

Soft-start devices reduce the level of voltage supplied to electric motors when they are first starting—a technique that typically reduces such undesirable start-up condition as high inrush currents and excessive starting torque. They are not speed controllers (they have no effect on the frequency of voltage supplied) but, rather, torque controllers. The major benefit of soft starters is a significant reduction in the shock to motors and loads that full-voltage starting can cause.

Soft-starters are often—and mistakenly—thought to reduce the energy required to start a motor and to also reduce a facility's peak demand charge because of the reduction in the peak amplitude of the inrush current. However, soft-starters do not reduce the amount of energy necessary to start a motor, rather, they redistribute it over a somewhat longer period of a few seconds rather than fractions of a second. This has no impact whatsoever on overall energy use and, because utility demand charges are usually calculated based on peak energy use within a window of at least 15 minutes, it is improbable that soft starting will reduce demand charges for most applications. On the contrary, the internal losses of a soft starter may actually contribute to an increase in demand charges.

# 6
# TECHNIQUES FOR EVALUATING ENERGY-SAVING POTENTIAL OF BLACK BOX PRODUCTS

Many users of electric power are approached by marketers of so-called energy-saving technologies that claim to significantly reduce energy use and to pay for themselves many times over. Sales presentations for these devices are often accompanied by claims of unique, patented technology innovations, rosy testimonials by enthusiastic purchasers, guarantees of performance, and other similar sales material. How can a facility manager or other potential buyer evaluate these myriad technologies and "separate the wheat from the chaff"? By employing two basic techniques: (1) by holding all purveyors of energy-saving technologies to a high level of proof, and (2) by being aware of the shortcomings of many of the most common techniques used by some marketers to make energy saving technologies look better on paper than they may be in real life.

## Evaluation Checklist for Energy-Saving Technology

When evaluating technologies that make energy savings claims, prospective buyers should use a rigorous series of questions to ascertain the credibility of the technology, its claims, and those who market it. In all cases, it is incumbent upon the marketers of energy-saving technologies to not only answer the questions that follow, but to *prove*—with a preponderance of clear and convincing evidence—that their technology and company are credible and worthy of consideration.

### *1. What Is the Mechanism for Saving Energy?*

Every electrical system has inefficiencies—whether manifest in the form of less-than-perfect energy conversion or in losses because of noise, vibration, or heat. Regardless, no technology can save more energy than is being wasted. Therefore, the first step in evaluating an energy-saving technology is to require specific documentation that (1) energy is, in fact, being wasted, and (2) that this energy can be saved if the proper technique is implemented.

For a number of technologies, answering this question is readily accomplished. For example, an induction motor-driven fan system operating at full speed, but with output throttled by inlet vanes offers a clear mechanism for energy savings: reduce the motor's speed, match the output of the fan to the needs of the process, and remove the inlet vanes.

In the case of power-factor-correcting capacitors, it can be readily demonstrated that electrical current moving through wires causes $I^2R$ losses and, by reducing the amplitude of the current, that these losses can also be reduced.

For energy savings from a TVSS, however, the energy savings mechanism is much less clear. To satisfy this question, a seller of TVSS purporting to save energy should be required to convincingly *document* that (1) many voltage spikes occur, (2) these voltage spikes overheat end-use devices, and (3) how much excess energy these overheated devices use. Without providing this level of documentation, it is extremely difficult to make an informed purchase decision.

It is, unfortunately, not uncommon for marketers of technologies that purport to save energy to present a smorgasbord of energy saving mechanisms, often including such sundry and diverse mechanisms as reduced reactive current, reduced harmonic current, improved voltage regulation, improved voltage unbalance, and ill-defined claims of “system balancing” and “matching output to the needs of the load.” It is the sole responsibility of the technology marketer to prove that each and every one of these claims is not only valid but of sufficient magnitude to be worthwhile.

### *2. How Does the Technology Implement the Energy-Saving Mechanism?*

Proving that an opportunity exists to save energy is a crucial first step, but it’s just the start. Next in the line of inquiry is to substantiate that the energy saving technology actually does something effective in reducing the losses. Or, put another way, does the technology actually *implement* the mechanism substantiated in Question 1 above?

When evaluating adjustable-speed drive (ASD) technology, for example, it can be readily demonstrated that the technology is capable of reducing the rotational speed of an induction motor and its load. Therefore, the savings mechanism of reduced speed is capably implemented by the technology.

For reducing losses in facility wiring, power-factor-correcting capacitors are also well known as effective tools in reducing reactive current in systems that have poor power factor.

For claims that TVSS can save energy, however, answering this question is a bit more difficult. Not only is it necessary to show that the particular surge suppression technologies are effective in reducing voltage spikes, it must also be shown that the TVSS technologies suppress voltage transients *sufficiently* to prevent excess heating in load devices.

### *3. Is the Value of Any Energy Saved Sufficient to Economically Justify a Purchase?*

Once the prospective purchaser has seen the technology vendor substantiate that there’s energy to be saved, and that the suggested technology actual goes about saving it, then it’s time to turn to economics. While this is familiar terrain for any technology purchaser, it is important to evaluate the economic impact of energy-saving technologies based on cost savings that are particular to each end-use facility, and not vendor literature.

Although ASD technology is capable of saving 50 percent or more of energy use in some installations, the actual load factor of the particular installation should be used.

Although some 1-2 percent of facility energy use *can* be attributed to losses in intra-facility wiring, levels of 0.5-1 percent are more common and available for savings by power-factor-correcting capacitors.

Some marketers of power-factor-correcting capacitors claim energy cost savings of as high as 10 to 25 percent—levels that are extremely difficult to substantiate. Some marketers of TVSS as an energy-saving technology promote claims of 20 percent savings on energy usage—levels that are also extremely difficult to substantiate.

### *4. How Does the Technology Compare with Competing and Alternative Technologies and Techniques?*

If the energy-saving technology has passed muster thus far, it then faces the most difficult hurdle of all: is it the most cost effective method to achieve the desired results? Unfortunately, technologies evaluators consistently overlook this question. What every purchaser of a technology really wants is to reduce energy costs at the lowest price, not to be the proud owner of any particular company's widget. However, the effort spent in doing due-diligence on one particular technology can blind evaluators to less costly, but equally effective alternatives.

For example, although the benefits may be attractive for addition speed control (using an ASD) to a motor-driven fan installation, for some installations a two-speed motor may be more cost effective and provide the same benefits.

For power-factor correction, there are many different manufacturers and packaging schemes for these systems, with a factor of 10 spread in their pricing. Does a facility need small, expensively packaged capacitors sprinkled throughout, or will one inexpensive capacitor bank at the service entrance provide the same benefits? If $I^2R$ losses are high in a facility, are the wires properly sized?

If a vendor of TVSS technology has satisfied demands for documentation of the energy-savings benefits of surge protection, then why not use the least expensive TVSS technology available? Alternatively, if the excess energy use is manifested by overheated equipment, perhaps the best approach is to improve the cooling of end use equipment, which may also be achievable at lower cost.

## Understanding the Shortcomings of Some of the Common Techniques for Marketing Energy-Saving Devices

Marketers of energy-saving devices often turn to a handful of techniques that, on the surface, appear to present a compelling case for purchase. However, a number of these techniques have serious shortcomings. Being aware of these shortcomings can empower the careful evaluator and enable an informed and, one hopes, profitable final decision on which technologies to pursue and which to leave by the wayside.

### *The Dangers of ``Before-and-After" Energy Use Comparisons*

It is quite common for marketers of energy saving technology to present data showing a facility's monthly energy bills before-and-after the installation of an energy-saving technology. Unfortunately, the two most common questions that purchasers of new technologies seek to answer—does the technology in question save energy? and, if so…how much?—are seldom answered by such a crude metric as the difference between before-and-after utility bills. Energy use at a facility is affected by too many variables, and utility bills provide too few data points, to allow for a valid before-and-after comparison.

The basic technique employed by marketers when using the before-and-after energy use technique is as follows: if a facility's energy use for a particular month was, say, 200,000-kWh, and a year later the energy use has dropped to, say, 180,000-kWh, the market would almost certainly claim that this entire 10 percent decline is attributable to a particular energy-saving technology installed during the intervening twelve months. To accept this claim as credible, however, one must accept the following difficult assumptions:

- **No Other Changes to the Facility's Behavior**: The central assumption in virtually all before-and-after energy use comparisons is that the addition of the energy-saving technology is the only variable of consequence. In fact, an untold number of variables regularly influence the amount of energy that a particular facility may use, including: changes in occupant or business activities; changes in the many types of equipment installed such as motors, lighting, and computers; changes in the behavior or use of these many types of equipment (such as how long ventilation systems, lights, or chillers are operated, or how efficiently air compressors or pumping systems function); changes in output because of the economic climate, and other similar factors.
- **The Energy-Saving Technology is the Dominant Contributor to Changes in Energy Use**: Even without major changes to the way a facility operates, other cyclical factors can influence how a facility uses energy, including outdoor temperature, humidity, and other weather; normal business cycles (number of weekends in a month, for example), normal seasonal variations (including number of holidays in the measurement period), and normal operation (and misoperation) of end-use equipment. In some cases, even the number of days in a billing cycle can vary depending on when meter-reading days fall. All of these factors can give the appearance of profound changes in energy use even if none exists.

Given the clear weaknesses of before-and-after bill comparisons, it is interesting to note how many marketers still cling to them as their main support for energy-savings claims. If stronger data existed, such as detailed audits by reputable third parties, rigorous laboratory testing, and other similar evidence, it would seem that those results would be featured and, thereby, sway more customers.

### *The Folly of Averages*

It is too common a practice, when trying to assess the effectiveness of a new technology or technique, to make a handful of measurements before the installation, and some after, and then to compare the averages of the before and after measurements to see if there is any change. This approach is attractive to many technology marketers, as well as end users, because it requires comparison of only two numbers—the before-and-after averages—and allows easy computation of the percent change. The dangers in this practice lie in three areas:

- **Loss of important information**. A significant amount of information is lost when multiple data points are boiled down to a single average number, such as how much variation existed within the original set of data points, or if the data was uniformly distributed, or clustered in some way. For example, comparing the average error in two lots of machined metal parts may show an improved average error in the second lot, but conceal that there are more rejected parts (parts that fail to meet minimum standards) in the second lot than in the first.
- **The average may not be a meaningful number**. Just because an average can be calculated does not mean it is a useful metric for evaluating performance. For example, some investor may find it interesting to compare the average rise or fall of the Dow Jones Industrial Average during odd versus even calendar years. These two averages can be easily calculated and even compared, but it is unlikely that they will provide any meaningful insight into how stocks will perform in the coming year.
- **An average is only as good as its original data**. One of the more common mistakes in comparing averages is that they are calculated from too few data points, or from data points that have been somehow "filtered" so that they are not a true random sample. In general, the more variability seen in the data, the more data points need to be gathered. While fewer data points may serve in some situations, a sample of 25 to 30 data points is generally considered adequate for most analyses.

### *"File Cabinet" Testing*

A common and seemingly irresistible technique for product marketing is to present to prospective buyers only those case histories that are most flattering to the technologies capabilities. This technique, known as "file cabinet" testing because all of the bad cases are left back in the office safely ensconced in the file cabinet, is disingenuous for a handful of reasons:

- **The spectrum of potential outcomes is skewed.** Selecting only the most attractive case studies for publication gives a false impression of certitude for excellent product performance. In reality, the performance of many energy-saving products ranges widely depending on the vagaries of each particular application.
- **Positive results could be nothing more than random chance.** One reason why good market researchers always insist on a random sample of a target population is to avoid the

problem of specially selecting a sample, and having that special selection yield up a false conclusion about the nature of the population as a whole. For example, if one were to survey 100 companies about their energy use this year versus last, some number (say, 1/3) would report higher energy use, another portion (say, another 1/3) could report lower energy costs, and the remainder might report little or no difference. To ignore those that report higher or same energy use and credit a particular technology with the "successes" of the lower energy use clients, would be a classic example of "file cabinet" testing.

**Extraordinary results are presented as "the norm."** Excluding less flattering results from information passed to what the prospective buyers creates greatly facilitates the tendency to have excellent, but unlikely results gradually take on the appearance of being the normal outcome or average result. An excellent example can be found in energy savings from power factor correction. Saving more that 1 percent of total facility energy through power factor correction is a very good and uncommon outcome. However, marketing literature for such devices commonly report examples where savings have been in this range or even higher, creating the impression that higher-level savings are available to all purchasers of the technology. In reality, most users will achieve less than 0.5 percent energy savings from power-factor correction.

# 7
# RECOMMENDATIONS

This report has been prepared to accomplish the following important objectives:

1. To provide guidelines for minimizing any undesirable power quality impacts of energy-saving technologies

2. To provide an understanding of the energy-savings potential of power quality-related technologies

3. To provide guidelines for evaluating “black box” technologies

What next steps are most imperative to furthering these objectives? An important first step is recognizing that energy efficiency and power quality are inseparable aspects of modern electric power systems, and it is becoming increasingly difficult to approach one problem without—positively or negatively—affecting the other. Users of energy-saving and power quality-improving products would benefit significantly from: (1) training and education, (2) technical resources and product testing, and (3) problem-solving resources for end users.

## Training and Education

The single most significant factor in the successful application of energy-saving and power quality-improving technologies in California is education—helping to foster and advance understanding among electric power end users of the opportunities for energy savings, reliable methods for addressing them, and the role that power quality plays in achieving success. Potential approaches to enhancing energy efficiency and power quality education include:

- **Web-Based Technical Information**: Providing comprehensive educational resources on the Internet such as: (1) materials on the range of energy-saving technologies and techniques and (2) materials covering power quality (PQ) and reliability topics, including definition of terms, description of typical problems, and basic explanation of potential solutions.
- **Web-Based Case Study Library**: Providing examples of real-world problems, how they were manifest, discovered, and solved.
- **Web-Based Solutions Guide**: A comprehensive database of existing energy efficiency and PQ technologies, including interactions, capabilities, reviews, problems addressed, and general sources for procurement.
- **Seminars**: One of the most effective techniques highlighted during interviews with California-based PQ professionals is the face-to-face seminar where technical and management personnel are educated on energy savings opportunities and the PQ and

reliability issues they raise. Interviews have provided at least anecdotal evidence that offering such seminars three to four times per year can dramatically improve end user awareness and understanding of important issues and increase awareness of important resources available to solve problems.

## Technical Resources and Product Testing

Many users of energy-saving and power quality-related technologies are eager for authoritative resources that can address the sorts of difficult questions addressed in this report. A number of technical resource areas exist that, if further developed and refined, could be of significant benefit to California businesses:

- **TVSS**: Testing and evaluation of Transient Voltage Surge Suppressors for effectiveness, energy-handing capability, and energy-savings capability.
- **Power-Factor Correction**: Testing and evaluation of the various techniques for improving power factor and for the impact that these techniques has on energy efficiency.
- **Energy-Saving Product Evaluation**: Testing and evaluation protocol for evaluation of important energy-saving technologies both for their effectiveness in reducing energy costs, but also for their impact on (or sensitivity to) important power quality parameters such as voltage sags and flicker, and harmonics.

## Problem-Solving Resources For End Users

Many electric power users have few or no resources for effectively solving vexing energy-saving and power quality-related problems. Often, they must rely on local contractors with little or no experience. Occasionally, end users are manipulated by consultants and unscrupulous vendors into paying many thousands of dollars for energy saving or power quality-improving technologies that are not based on sound science or proven technologies. These end users would benefit from having an unbiased resource to which to turn to provide assessments of the best approaches for balancing energy savings and power quality, and to evaluate existing installations of technologies and to ascertain their effectiveness.